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PCEMCAN—Probabilistic Ceramic Matrix Composites Analyzer

User's Guide, Version 1.0

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TABLE OF CONTENTS

0.0 FOREWORD

PCEMCAN (Probabilistic CEramic Matrix Composites ANalyzer) is an integrated computer code developed at NASA Lewis Research Center that simulates uncertainties associated with the constituent properties, manufacturing process, and geometric parameters of fiber reinforced ceramic matrix composites and quantifies their random thermomechanical behavior. The PCEMCAN code can perform the deterministic as well as probabilistic analyses to predict thermomechanical properties. Various levels of composite mechanics models (sub-structuring) built into the code allow comprehensive point analysis of composite behavior whereas the perturbation analysis and the fast probability integration algorithms quantifies behavior uncertainties at all scales.

The deterministic version of the code, called CEMCAN (ref. 1), now expanded into PCEMCAN, originated as an adaptation of ICAN (Integrated Composites Analyzer, ref. 2) and METCAN (Metal Matrix Composites Analyzer, ref. 3) computer codes previously developed at NASA Lewis Research Center for polymer matrix composites and metal matrix composites respectively. Hence, current users of the ICAN and METCAN computer codes will recognize similarities with respect to code structure, input/output format, etc. However, there are substantial fundamental differences between CEMCAN and the other two codes (ref. 4).

The PCEMCAN code integrates CEMCAN and the FPI (Fast Probability Integrator) module of NESSUS (Numerical Evaluation of Stochastic Structures Under Stress, ref. 5) computer code. NESSUS is a computer code developed under the NASA Lewis Research Center sponsored program "Probabilistic Structural Analysis Methods." The PCEMCAN integration includes the automated perturbation and probabilistic analysis to perform the probabilistic simulation of the ceramic matrix composite properties and strengths. PCEMCAN can be used to perform deterministic as well as probabilistic analyses.

The following sections provide a step-by-step outline of the procedure necessary to utilize both deterministic and probabilistic options of PCEMCAN, i.e., the preparation of input data and a sample constituent materials resident data bank. The constituent material data bank contains the mechanical and the thermal properties of generally available fiber, matrix and interphase which can be modified and updated as described in the manual.

1.0 PCEMCAN CODE ANALYSIS CAPABILITIES/FEATURES

This version of the PCEMCAN computer code contains the following features:

1.1 Deterministic Analysis

(i) The code can predict ply and laminate properties, micro-stresses and the stress/strain behavior up to failure of a composite laminate.
(ii) A nonlinear capability that includes micro-stress redistribution as a result of crack initiation and progression is available in PCEMCAN.
(iii) It is possible to account for constituent material non-linearity (e.g., constituent property dependence upon temperature) via the use of a multi-factor interaction relationship that accounts for simultaneous interaction of various effects on in-situ material behavior.

(iv) Another capability available in PCEMCAN is the incorporation of a process related load profile prior to the application of any thermal and/or mechanical loading. Thus, the stresses and strains resulting from the processing of a composite can be accounted for if desired by the user.
(v) The structure of the constituent data bank makes the modification or expansion of the data bank much simpler.
(vi) Several print options are available in the code so that the user can tailor the output to his/her needs. These include control of what output is desired and at what reporting frequency i.e. printing of desired output after a certain number of load steps have been analyzed.
(vii) A capability to include comments within the input file itself is available in the code.

1.2 Probabilistic Analysis

(i) Computational simulation of uncertainties in the primitive random variables to predict cumulative distribution function (CDF) of composite thermomechanical properties using fast probability integration.
(ii) The code can quantify the sensitivities of the input primitive random variables to the composite thermomechanical properties.
(iii) A conventional Monte-Carlo simulation of primitive random variables and computation of composite thermo-mechanical properties CDF can be performed. It is to be noted that the Monte-Carlo simulation is computationally intensive. The run time is directly proportional to the number of samples used. Therefore, it may be used for verification purposes or in the event that the FPI algorithms do not converge.
(iv) The primitive random variable distributions allowed are: normal, Weibull, Lognormal, extreme value, chi-square, Frechet.
(v) The CDF and probabilistic sensitivity of more than one composite property can be computed in one single run.

The potential user of PCEMCAN is reminded that the development is in the evolutionary state and the methodology is of an ongoing research nature. Many more probabilistic algorithms such as advanced mean value, iterative advanced mean value, second order second moment reliability analysis, fast Monte-Carlo methods will be included as the need arises.

Questions that pertain to the theoretical aspects and utilization or feedback regarding PCEMCAN computer code should be directed to the authors.

2.0 SYMBOLS AND UNITS

Subscripts

c	Composite (laminate) related quantity
l	Ply (lamina) related quantity
s	Slice (fiber substructured unit) related quantity
i	Interphase related quantity
f	Fiber related quantity
m	Matrix related quantity
X,Y,Z	Structural coordinate system axes
1,2,3	Material coordinate system axes

Symbols

N	In-plane stress resultant (lb/in)
M	In-plane moment resultant (lb-in/in)
P_U, P_L	Laminate upper and lower surface pressures (psi)
Q	Out-of-plane shear resultant (lb/in)
t	time (seconds)
T	temperature (^{o}F)

List of abbreviations

CDF	Cumulative probability distribution function
COV	Coefficient of variation
FPI	Fast probability integrator
MFIR	Multi-factor interaction relationship
PDF	Probability density function
RVE	Representative volume element
RHO	Density of material
CTE	Coefficient of thermal expansion
HK	Heat conductivity
HC	Heat capacity
E	Modulus of elasticity
NU	Poisson's ratio

3.0 THEORETICAL BACKGROUND

3.1 Ceramic Matrix Composite Micro/Macro Mechanics

In-house research at NASA Lewis Research Center in Cleveland, Ohio over the past twenty years has focused on simplified micromechanics equations and has culminated in several computer codes for composite micro- and macromechanics. Notable among those codes are ICAN (Integrated Composite ANalyzer, ref. 2) that was developed primarily for analyzing polymer matrix composites, and METCAN (METal Matrix Composite ANalyzer, ref. 3) which was developed to analyze and predict the behavior of metal and intermetallic matrix composites. The micromechanics in ICAN computer code is based on a unit cell or representative volume element (RVE) (fig. 3.0.1) which assumes that the fibers are arranged in a square array pattern. The unit cell consists of fiber and matrix and a perfect bond is assumed between the two constituents. Simplified micromechanics equations are used that describe the equivalent unit cell properties in terms of the thermal and mechanical properties of the constituents and the fiber volume ratio (fvr). The METCAN code uses the same general philosophy of simplified micromechanics equations and also assumes the fibers to be arranged in a square pattern array. However, in the case of METCAN the unit cell or RVE (fig. 3.0.1) can consist of three constituents - fiber, matrix and an interphase or a compliant layer. The third constituent is unique to this class of materials. It can develop as a reaction-zone (interphase) due to a possible chemical reaction between the fiber and the matrix, or it could be a fiber coating or a compliant layer to prevent the formation of above-mentioned reaction-zone or interphase region. In any case, the interphase region is a distinct region with a finite width/volume ratio and the formulation in the code allows this region to have mechanical and thermal properties that can be different than those of the fiber or matrix.

In the application of this approach to ceramic matrix composites, the unit cell or RVE (fig. 3.0.1) is further subdivided into several slices and the simplified micromechanics equations are applied to each slice in order to get the equivalent slice properties in terms of constituent properties (ref. 6). These slice properties are subsequently integrated to obtain the equivalent unit cell or ply properties by the application of laminate theory in an identical way as one would get the equivalent or homogenized composite properties from ply properties. This novel modeling technique has been referred to as the fiber sub-structuring technique and is available into the PCEMCAN (Probabilistic CEramic Matrix Composite ANalyzer) code for analyzing and predicting the behavior of ceramic matrix composites. Such a technique allows for a more accurate micro-mechanical representation of interfacial conditions, and provides a greater detail in stress distribution within a ply. Figure 3.0-2 shows the integrated analysis approach embedded in the PCEMCAN computer code. The left side of the chart shows the "synthesis" of the properties from slice to ply and then to laminate properties. The right side of the chart shows the "decomposition" of response from laminate stresses to ply stresses, then to slice stresses and finally microstresses in each constituent. Any nonlinearity in the material behavior is accounted for at the constituent level. It should be noted that one of the major purposes of reinforcing ceramic matrices is to increase their toughness and eliminate catastrophic failures by enabling such toughening mechanisms as fiber debonding, fiber bridging, fiber pullout, crack deflection etc. The interphase plays a very important role in these mechanisms and hence, requires an accurate micromechanical model. Related theory, micromechanics equations for fiber sub-structuring and microstress equations that relate the homogenized slice stresses to constituent stresses are published in a companion document (ref. 6).

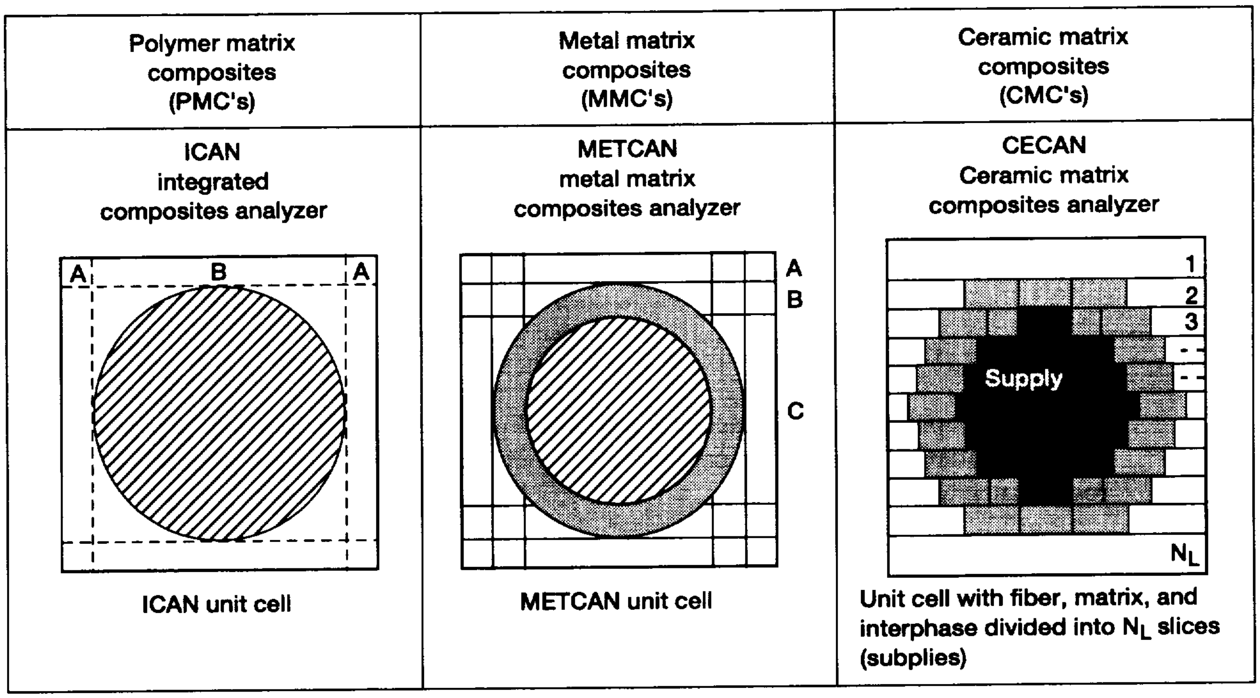

Figure 3.0.1.—Micromechanics for composite.

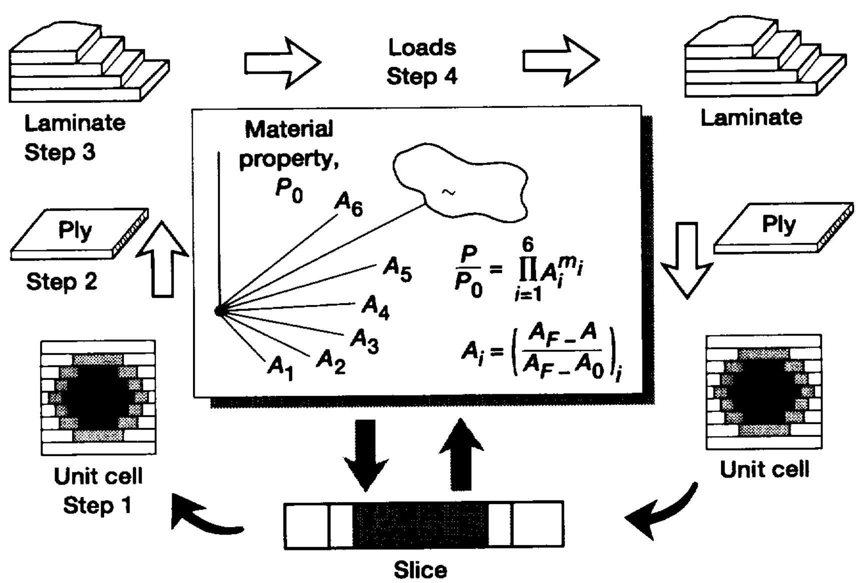

Figure 3.0.2.—Integrated analysis in CEMCAN.

3.1.1 Nonlinear Constitutive Material Model

PCEMCAN treats material non-linearity at the constituent level through the use of a multi-factor interaction relationship (MFIR). The MFIR models the phenomenological material behavior in the form of a time-temperature-stress dependence of the constituent properties. The MFIR relationship is expressed in the form of an equation:

$$\frac{P}{P_o} = \left[\frac{T_F - T}{T_F - T_o}\right]^n$$

where P - Property, P_o- Reference property, T_F - Final temperature (generally this is a melting temperature), T-Current temperature and T_o - Reference temperature (generally this is room temperature)

The form of the MFIR is a product function of terms raised to specified powers that define the values of the material property (P) of the constituent. Mechanical, thermal or strength values of all constituents can be degraded through the use of MFIR. For each constituent, a distinct set of exponents is generally necessary to express the functional value of that property. The exponent should be determined from the available experimental data. However, default values should be used if measured values to determine the actual values of exponents are not available. The default values of exponents are defined for various fibers, matrices and interphases and are shown later in the resident sample constituent databank (section 5.2).

3.2 Probabilistic Simulation

There are a number of approaches available for obtaining probabilistic response from a set of independent variables and the expressions describing the response behavior. Monte-Carlo simulation is one such fairly common approach to obtain the CDFs of composite properties, given the probability distributions of constituent properties, which are considered as independent variables. In this technique, randomly selected values of the input variables based on their known probabilistic distributions are used to compute the value of the response variable deterministically. Usually this is repeated several hundred times to build the probabilistic characteristics of the response. In essence, this technique requires a large number of simulations to generate CDFs of output variables. Although inherently simple, the large number of output sets that must be generated to obtain a reasonably accurate CDF of output variables becomes its obvious disadvantage. Furthermore, if the deterministic computation of the response is complicated and time-consuming, the computational costs could become prohibitive. Obviously, to circumvent expensive and time-consuming computational procedures, more efficient approaches and algorithms are needed.

For more than a decade NASA Lewis Research Center has been engaged in developing efficient probabilistic methods. As a result of this intensive program, FPI (ref. 7) was developed to solve a large class of engineering problems. The following paragraphs describe the problem to be solved and how FPI was used to investigate the probabilistic behavior of ceramic composites.

Suppose that there are n random variables in a problem and it is desired to compute the probability of occurrence of a certain response function:

$$Z(X) = Z(X_1, X_2, \dots X_n) \tag{3.2.1}$$

where Z represents the response variable and X_i represents the ith random variable. One of the objectives of the probabilistic analysis is to compute the probability that Z will have a value less than or equal to a given magnitude Z_o (Z_o may be referred to as a limit value). To achieve this goal, the performance function (eq. 3.2.1), which describes how the system behaves, can be cast as a limit state function $g(X)$, described as

$$g(X) = Z(X) - Z_o \tag{3.2.2}$$

Thus, the objective would be to compute $P[g(X) \leq 0]$. In the case when Z_o describes a limit indicating failure, $g(X)$ is called a failure function, e.g., the probability of stress exceeding the strength.

Given the probability density function $f_x(x)$ of the random variables one can formulate the limit state probability $P[g \leq 0]$ as

$$P_f = P[g(X) \leq 0] = \int_{\Omega} \dots \int f_x(X) dx \tag{3.2.3}$$

where Ω describes the domain of integration (failure region). In general, it is very difficult to evaluate the above multiple integral analytically. However, FPI has been found to be an excellent tool to evaluate equation (3.2.3) efficiently and accurately.

FPI is a probabilistic analysis tool that implements a variety of methods for probabilistic engineering analysis and design (see schematic in fig. 3.2.1). In general, FPI requires the following:

(1) The definition of the independent and uncorrelated input (design) variables and their probability distributions. Constituent properties, FVR, void-volume ratio (VVR), ply thickness, ply alignment, etc. are independent random variables. In equation (3.2.1), X represents these variables.
(2) A function (called the performance function) that defines the relationship between the response variable and the independent random variables is required for FPI analysis. Ply or laminate properties are the response variables in PCEMCAN. Composite micro/macro mechanics in PCEMCAN evaluates the performance function. In equation (3.2.1), variable Z is a dependent variable whose uncertainties are required to be computed.

Probability distributions of independent variables in PCEMCAN can be obtained from the available measured data or can be assumed on the basis of experience and judgment. For most problems, it is difficult to determine analytical expressions representing a relationship between independent and dependent variables. In the case of CMC's, it is very complicated to build relationships for the ply or laminate properties as a function of constituent properties, fabrication parameters, and such. PCEMCAN has a built-in capability to form such relationships, using micromechanics and macromechanics theory (ref. 8). A performance function is developed by using a numerical approach. In this approach an explicit response function is developed by perturbing the independent random variables about their mean values and using PCEMCAN to compute the response. Discrete evaluations of the response variables for the perturbed values of independent variables are then fit into a function using regression analysis. The uncertainties of a response variable is quantified in the form of a CDF by the following procedure:

(1) The primitive variables and the corresponding probabilistic distributions are selected. (For example, to generate the CDF of a composite longitudinal modulus, the primitive variables could be the fiber modulus, matrix modulus, FVR, and so forth.) For a given set of values of primitive variables, the micromechanics and macromechanics in the PCEMCAN computer code are used to compute the desired response variable.
(2) The whole process is repeated to generate a table of response variable values that correspond to the perturbed values of primitive variables.
(3) The FPI analysis then uses the previously generated table to compute the CDF and the corresponding sensitivities of the response. FPI computes the CDF of the response variable and the probabilistic sensitivity factor. Several methods can be used to compute a CDF.

In addition to the CDF of a response, FPI provides additional information regarding the sensitivity of the response with respect to the primitive variables. Sensitivity information is very useful for studying the probabilistic variation of the response. The sensitivity referred herein is a probabilistic sensitivity and it provides the information on how the reliability changes with respect to the change in the primitive variable uncertainty. The detailed theoretical information on sensitivity is given in reference 7.

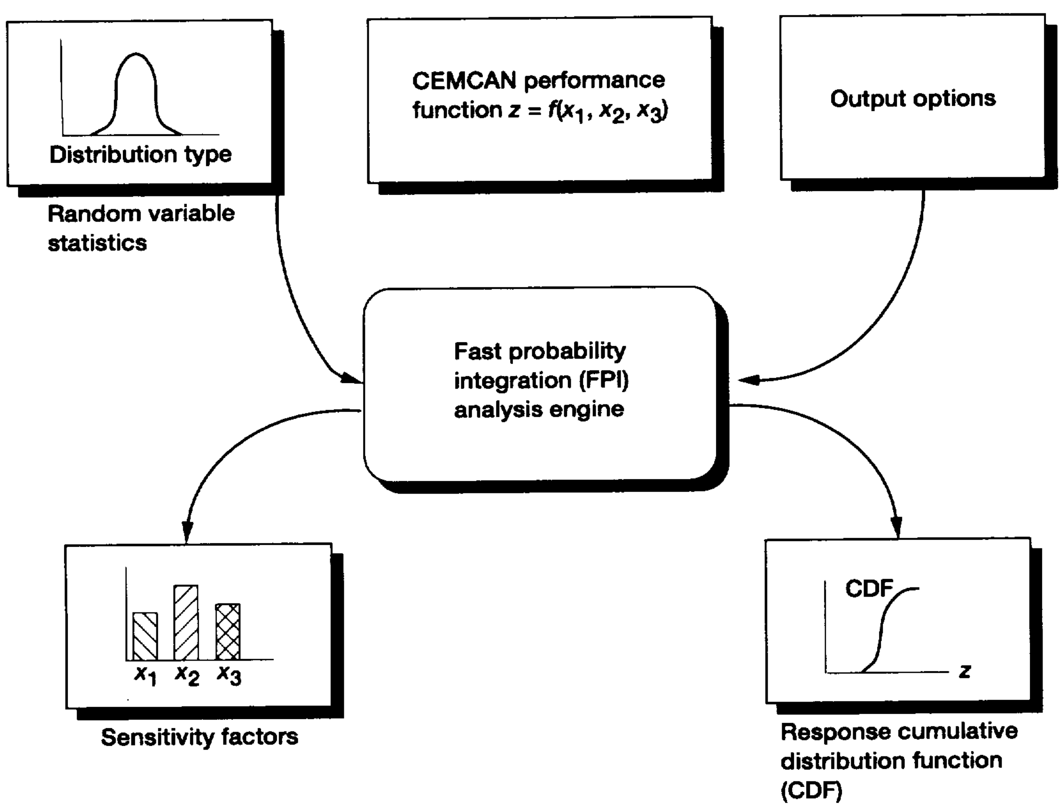

Figure 3.2.1.—Fast probability integration input-output schematic.

4.0 PCEMCAN CONVENTIONS

The global and local coordinate systems employed in PCEMCAN and the conventions for ply ordering, measuring orientation angle, and loading are presented in the following sections.

4.1 GLOBAL (LAMINATE) COORDINATE SYSTEM

Figure 4.1-1 shows the global or laminate coordinate system for an arbitrary laminate. In this convention, the global X-axis is oriented parallel to the fiber direction of a 0° ply, the Y-axis is oriented perpendicular to this fiber direction and Z-axis is oriented through the thickness direction of the laminate. Plies are always in the X-Y plane. X, Y, Z are also referred to as structural axes, or the global or laminate coordinate system.

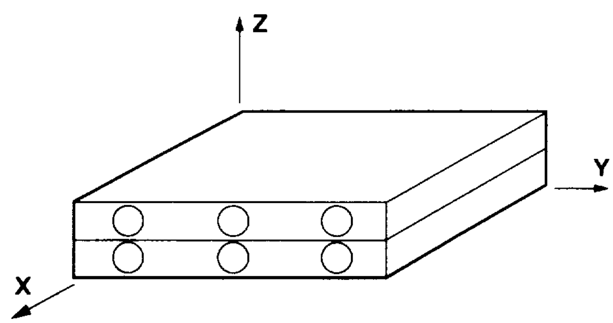

Figure 4.1.1.—PCEMCAN global (laminate) coordinate system.

4.2 LOCAL (MATERIAL) COORDINATE SYSTEM

The local or material coordinate system is shown in figure 4.2-1. The 1-axis is oriented parallel to the fiber direction in the ply, the 2-axis is oriented perpendicular to this fiber direction, and the 3-axis is oriented through the thickness dimension of the ply.

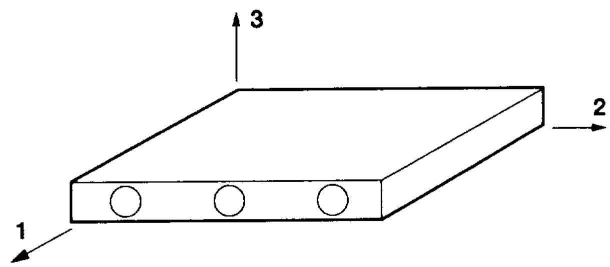

Figure 4.2.1.—PCEMCAN local (material) coordinate system.

4.3 PLY ORDERING CONVENTION

The ply ordering convention employed in PCEMCAN is shown in figure 4.3-1. The first ply is placed at the bottom of the X-Y plane at Z=0. Subsequent plies are stacked on top of the first ply in the positive Z direction.

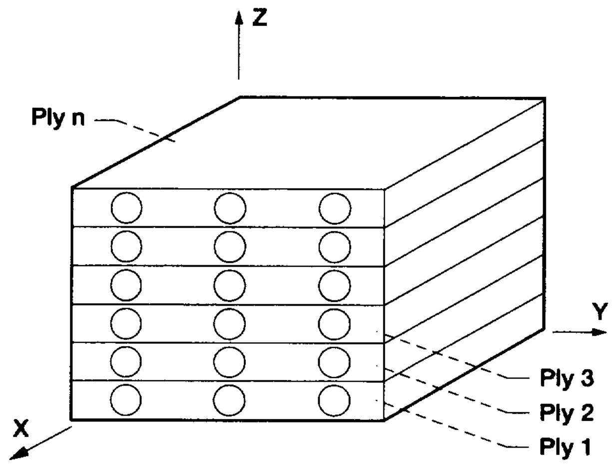

Figure 4.3.1.—PCEMCAN ply ordering comvention.

4.4 PLY ORIENTATION ANGLE CONVENTION

The orientation angle of a ply is taken as the angle between the local coordinate system and the global coordinate system, as shown in figure 4.4-1. The convention for positive is the angle measured counter-clockwise from the X-axis.

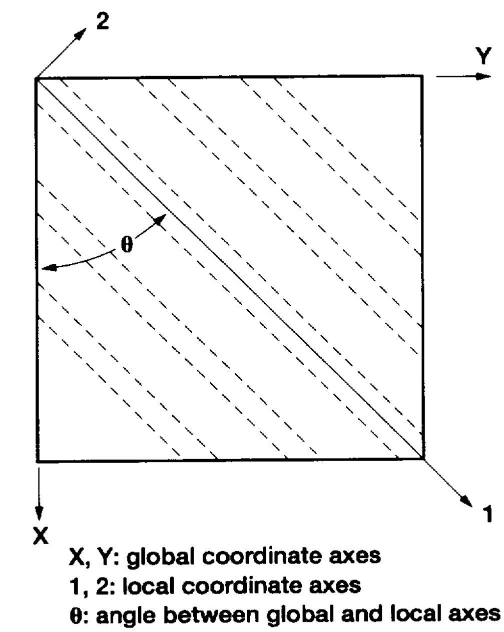

Figure 4.4.1.—PCEMCAN ply orientation angle convention.

4.5 LOADING CONVENTION

The positive sign conventions for the various loadings in PCEMCAN are presented in figure 4.5-1. It should be noted that the PCEMCAN input file assumes stresses and moments to be integrated resultant quantities in the usual sense of the plate and shell theory. Force resultants are represented by force per unit width, while moment resultants are moments per unit width. The in-plane force resultants are N_x, N_y, N_{xy}, while out-of-plane force resultant are represented by Q_{xz} and Q_{yz}. Moment resultants are symbolized by M_x, M_y and M_{xy} and the upper and lower surface pressures are denoted by P_u and P_l respectively.

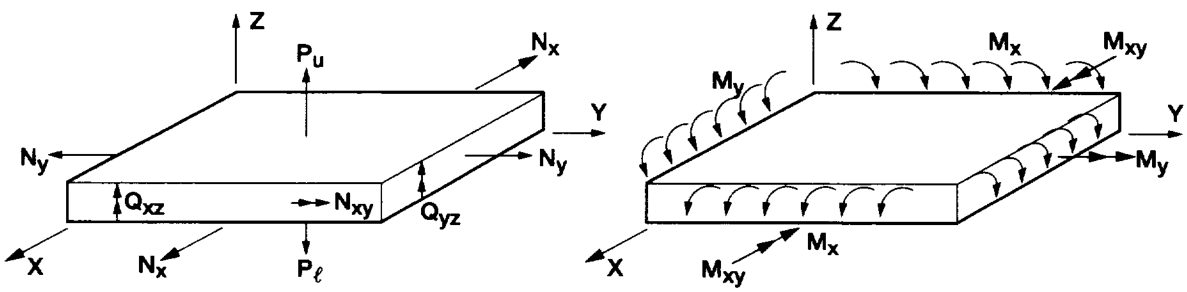

Figure 4.5.1.—PCEMCAN positive loading convention.

5.0 PCEMCAN INPUT FILE AND DATA RECORDS DESCRIPTION

The execution of PCEMCAN requires input describing the composite geometry, constituent material properties, load profiles, output options, and the uncertainties associated with the primitive variables (uncertainty data is not required for deterministic analysis). Parameters required to define primitive variable uncertainties are the mean, standard deviation/coefficient of variation and its probability distribution type. In order to minimize the entry of input, a resident material data bank file containing constituent properties has been created. Thus the input required for PCEMCAN has been divided into two files: pcemin.dat (primary input file) and new.dbk (material data bank). The primary input file contains the input related to laminate geometry, material system definition, load profile, and output options whereas the data bank contains constituent material properties. Normally the user modifies the input file. However, the material data bank is modified only if the properties of the material are different or when new materials are to be added.

5.1 PRIMARY INPUT FILE STRUCTURE

The primary input file consists of three major sections (fig. 5.1.1) (i) control data, (ii) deterministic data, and (iii) probabilistic data. Such a file structure separates the deterministic and probabilistic input data. The first section of the file contains the title card and a keyword indicating whether deterministic analysis or probabilistic analysis is to be performed. Users desiring to run deterministic analysis do not have to input the data required for the probabilistic analysis as described in section 5.1.3. However, for the probabilistic analysis option, data in all the three sections must be input. Any record with a "$" sign in the first column can be used to insert comments anywhere in the input file. Deterministic input data format follows a specific order and fixed FORTRAN input. However, most of the probabilistic input data can be input in any order and a free format.

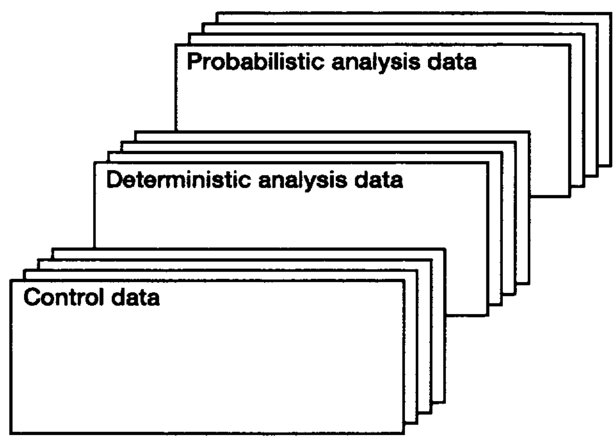

Figure 5.1.1.—Primary input file structure.

5.1.1 Control Data

This section of the input file requires two records and must be input in the order listed below (fig. 5.1.1-1):

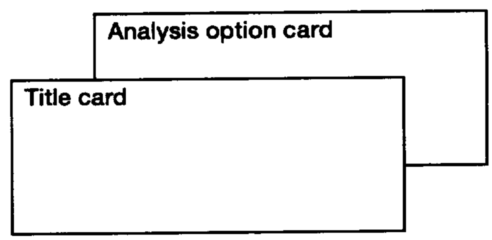

Figure 5.1.1.-1—Control data card sequence.

5.1.1.1 Title Record (A80)

Any string up to 80 characters long can be entered.

5.1.1.2 Analysis Control Record (A4)

The legal keywords are listed below and can be selected for the desired analysis:

DETE	-	For the deterministic analysis
PROB	-	For the probabilistic analysis

5.1.2 Deterministic Analysis Data

All the input records listed in this section are required in the specified order and format. Each record can be composed of one or several lines of data. Each line of data has a fixed format of eight column fields. Integer and exponential formats must be right justified within the field, while floating point format can be entered anywhere within the field. Description of each record with simple examples is given in this section. The input record sequence is given in figure 5.1.2-1.

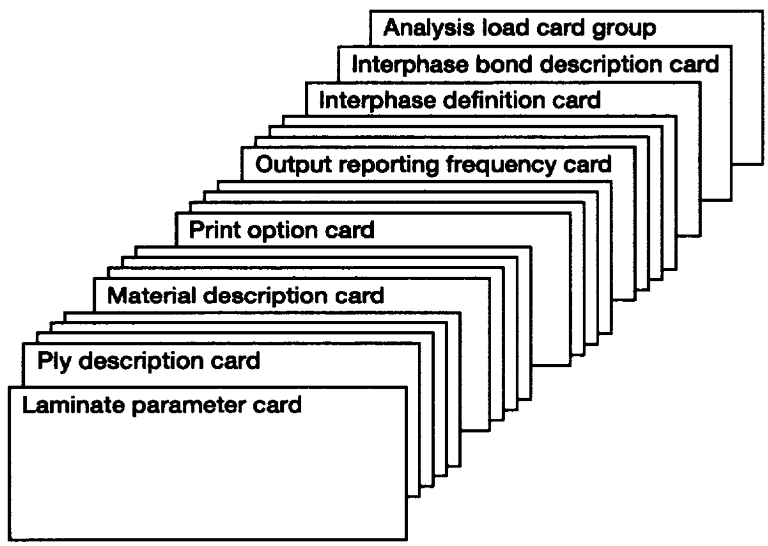

Figure 5.1.2-1.—Deterministic analysis data sequence.

5.1.2.1 Laminate Parameter Record

NPLY NMS NFBDIV (318)

This card defines the total number of plies (NPLY), the number of material systems (NMS) and the number of fiber divisions (slices, should be an odd number) including the interphase desired in the problem (NFBDIV = Number of fiber divisions +2 (for interphase)), preferably < = 9 (Refer to fig. 5.1.2.1-1).

EXAMPLE:
3 1 7

This example shows three plies, one material system and seven slices in the fiber and interphase (five slices in the fiber and two in the interphase)

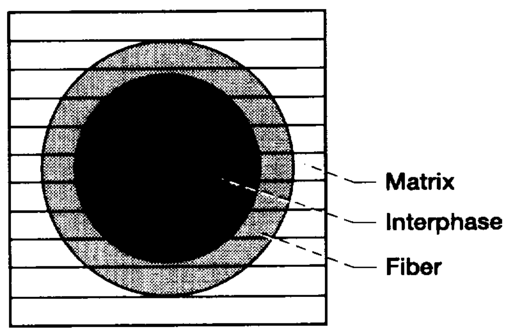

Figure 5.1.2.1-1.—Unit cell substructuring (NFBDIV = 7).

5.1.2.2 Ply Description Record

PLY NO. MATERIAL ID ANGLE THICKNESS (A8,2I8,2F8.3)

Each ply of the composite is defined by a separate line, with five entries as shown above. The first field contains the mnemonic PLY. The second and third fields contain identification numbers for the ply and composite material system for that ply, respectively. The fourth and fifth fields contain the orientation angle of the ply material coordinate system with respect to the structural coordinate system and the thickness of the ply, respectively.

EXAMPLE:

```
PLY    1      1      45.0     0.005
```

In the above example, for ply no. 1, the material id no. is also 1. The ply is oriented at 45° (see section 4.4) from the structural X-axis and is 0.005 in. thick. <u>The number of records in this group should be same as the total number of plies.</u>

5.1.2.3 Material Description Record

MATCRD MATID FVR VVR FIBRMTRX (A8,I8,2F8.2,2A4)

Each different composite material system is defined by a separate card, containing five entries. The first field contains the mnemonic MATCRD. The second entry is the material system identification number. The third and fourth fields contain the fiber volume fraction and void volume fraction respectively. The last field contains the four character "code-names" for the fiber and the matrix material of a particular composite system. These code names identify the fiber and matrix in the resident materials data bank. More details on the code names is described in section 5.2 of this manual.

EXAMPLE:
```
MATCRD    1   0.3   0.0SICRRBSN
```

In this example, this material system with ID = 1, contains 30 percent fiber volume ratio and no voids. The fibers are identified by a four letter code SICR and the matrix by RBSN in the data bank. If such material with these code names are not included in the data bank, the program will stop after writing an error message in the output file.

5.1.2.4 Print Options Record

PRINT Option (2A8)

User controlled output reporting is possible by using this group of records. Each output option is specified by a separate record containing two entries. The first field contains the mnemonic PRINT and the second field contains the mnemonic for the desired option or options. Currently, the following output options are available:

Option	Output Information
ALL	Complete output is reported
CONSTI	Laminate constitutive relationship
DISPFOR	Displacement-force relationships
LDSTEP	Information for current load/time step
MICRO	Constituent total stresses for each slice of every ply
NONE	Output reporting suppressed
PLYRESP	Ply properties and ply responses
PLYSTRS	Ply stresses and strains
PROPCOM	Laminate 2-D and 3-D properties
PROPREF	Constituent reference properties
STRSTRN	Laminate stress-strain relationships and MSC/NASTRAN MAT9 card

There is no limit to the number of output options which can be requested. However, each output option requires a separate record. This record does not control the output reporting frequency which is controlled through the PRINTOPT card.

NOTE: These options are operational only when deterministic analysis is being performed. However "PRINT NONE" card must be input for the probabilistic analysis input. Probabilistic analysis requires several perturbations and the output file could become extremely large. To avoid generations of huge output files, these print options are suppressed during probabilistic analysis. However, useful options may be turned on for probabilistic analysis in future versions of the code.

5.1.2.5 Output Reporting Frequency Record

PRINTOPT Option (A8, A8 or I8)

This record controls the output reporting frequency for the output options chosen above. There are two entries in this record. The first entry is the mnemonic PRINTOPT. There are three choices for the second entry:

(i)	ALL	Output is reported for each load-step of the analysis
(ii)	LAST	Output is reported for the last load-step of the analysis
(iii)	I (integer)	Output is reported for every I-th load-step of the analysis

NOTE: These options are operational only when deterministic analysis is being performed. Probabilistic analysis requires several perturbations and the output file could become extremely large. To avoid generations of huge output files, these print options are suppressed during probabilistic analysis. However, useful options may be turned on for probabilistic analysis in future versions of the code.

5.1.2.6 Interphase Definition Record

INTRFACE INTR TD (A8, I8, F8.2)

The user can specify the existence of a discrete interphase between the fiber and the matrix by means of this card. The first field contains the mnemonic INTRFACE. The second entry consists of indicator 0 or 1 indicating whether an interphase is to be considered in the analysis. A value of 1 indicates that an interphase is to be considered while a value of 0 indicates that no interphase is to be considered. Currently, the code should be run with this value as 1, i.e. an interphase should be present. The thickness of the interphase is specified in the third field as a fraction of the fiber diameter. PCEMCAN will retrieve material properties for the interphase that correspond to the interphase thickness specified by the parameter TD and not by code name. <u>A current restriction allows only one interphase type to be specified in an analysis and it is taken to be identical for every ply</u>.

```
EXAMPLE:
INTRFACE          1            0.05
```

The above example shows that an interphase is to be considered in the analysis and its thickness is 5 percent of the fiber diameter.

<u>Note</u>: The value of INTR should always be entered 1 for the current version of the PCEMCAN computer code.

5.1.2.7 Interphase Bond Description Record

FACT2(NL,I)	(10F8.2)
FACT3(NL,I)	(10F8.2)

This record group describes the interphase bond. The first line, FACT2, defines the bond in every slice based on 2-2 sub-structuring (fig. 5.1.2.1-1) starting from the interphase slice (the first slice consists of matrix only). <u>One set of records or two lines per ply should be provided to describe the interphase bond.</u>. The value of these coefficients can be anywhere from 0.0 (no bond) to 1.0 (perfect bond). For example, if a coefficient for a specific slice is 0.5, then the normal and shear modulii for the interphase for that particular slice will be 0.5 times the value provided in the resident data bank. Fact 3 are similar factors for slices based on 3-3 sub-structuring.

Note that the number of slices for the 2-2 and 3-3 sub-structuring will be the same. For example, if one wants 5 fiber divisions (slices), then NFBDIV = 5 + 2 = 7 (5 for fibers and 2 for interphase) and the total number of slices then will be 9 (see fig. 5.1.2.1-1). Fact2 and Fact3 should be defined for all slices 2 to 8 (total of 7 slices).

EXAMPLE:

```
1.0   0.5   1.0   1.0   1.0   1.0   1.0
1.0   1.0   1.0   0.5   0.2   1.0   1.0
1.0   1.0   1.0   1.0   1.0   1.0   1.0

1.0   1.0   1.0   1.0   1.0   1.0   1.0
1.0   0.5   1.0   0.5   0.3   1.0   1.0
1.0   1.0   1.0   1.0   1.0   1.0   1.0
```

This example assumes that there are three plies and each ply has five slices in the fiber and two in the interphase (NFBDIV = 7). The slice 2 of ply 1, slice 4 of ply 2 and slice 5 of ply 2 respectively have 50%, 50% and 20% bond in sub-structuring direction 22, whereas the slice 2 of ply 2, slice 4 of ply 2 and slice 5 of ply 2 respectively have 50%, 50% and 30% bond in sub-structuring direction 33. A value of 1.0 indicates full interphase values for the remaining slices in 22 and 33 direction.

5.1.2.8 Analysis Load Record Group

TMLOAD -NLS (A8,I8)

The first record in this group contains two entries. The first entry is the mnemonic TMLOAD. The second entry is a negative integer (-NLS). NLS stands for the number of load segments to define a piece-wise linear loading history. For example, if the effects of processing are to be included in a simulation prior to the application of mechanical or thermal loading, the value of NLS can be 2. The first segment then will represent temperature and pressure profile of the processing, while the second linear segment will represent the applied thermal and/or mechanical loading.

Each load segment requires a series of records as described below:

(i) t_i t_{i+1} INCR (2E8.2,I8)

The first entry (t_i) is the starting time, t_{i+1} is the ending time for this load segment and INCR is the number of increments (load steps) that this segment is divided into. The value of INCR depends on the behavior of material with respect to load/temperature.

(ii) $T_{1,i}$ $T_{2,i}$ $T_{3,i}$ .... (10E8.2)

T_1 is the temperature of ply 1 <u>at time ti</u> (beginning of the load segment), T_2 is the temperature of ply 2 <u>at time ti</u> and so on. <u>If there are more than 10 plies</u>, then continue on next line.

(iii) $T_{1,i+1}$ $T_{2,i+1}$ $T_{3,i+1}$ .... (10E8.2)

T_1 is the temperature of ply 1 <u>at time t_{i+1}</u>, T_2 is the temperature of ply 2 <u>at time t_{i+1}</u>, and so on.

(iv) $N_{x,i}$ $N_{y,i}$ $N_{xy,i}$ $M_{x,i}$ $M_{y,i}$ $M_{xy,i}$ $Q_{xz,i}$ $Q_{yz,i}$ $P_{l,i}$ $P_{u,i}$

(10E8.2)

This records contains global in-plane force resultant, in-plane moment resultant, transverse shear resultant, lower and upper surface pressures <u>at time t_i</u>

For the sign convention of the loading, see the section no. 4-5.

(v) $N_{x,i+1}$ $N_{y,i+1}$ $N_{xy,i+1}$ $M_{x,i+1}$ $M_{y,i+1}$ $M_{xy,i+1}$ $Q_{xz,i+1}$ $Q_{yz,i+1}$ $P_{l,i+1}$ $P_{u,i+1}$

(10E8.2)

This record contains global in-plane force resultant, in-plane moment resultant, transverse shear resultant, lower and upper surface pressures <u>at time t_{i+1}</u>

<u>Important</u>: This set of cards (i) through (v) should be repeated for each load segment. An example is shown in section 7.1 for input analysis load records.

5.1.3 Probabilistic Analysis Input Data Record Description

The input described in this section is required only if the probabilistic analysis option in section 5.1.1.2 is chosen. The probabilistic input requirement in this section is different from the deterministic input in that it is free format and order independent. The variables can be input in terms of words or symbols and the characters in the input are case insensitive. A list of primitive variable names and their symbols are given in Table 5.1.3.1. Delimiters separating the numbers or parameters can be either a space, " ", or a comma.

TABLE 5.1.3.1.—PRIMITIVE VARIABLE NAMES AND THEIR SYMBOLS

Ply description primitive variables	
Ply thickness	plth
Ply angle	pang
Fabrication variables:	
Fiber volume ratio	FVR
Void volume ratio	VVR
Interphase thickness	ti
Constituent properties primitive variables:	
Fibers	
Normal modulus 11	Ef11
Normal modulus 22	Ef22
Poisson's ratio 12	nuf12
Poisson's ratio 23	nuf23
Shear modulus 12	gf12
Shear modulus 23	gf13
Coefficient of thermal expansion 11	alfaf11
Coefficient of thermal expansion 22	alfaf22
Thermal conductivity 11	kf11
Thermal conductivity 22	kf22
Heat capacity	cf
Tensile strength 11	sf11t
Tensile strength 22	sf22t
Compressive strength 11	sf11c
Compressive strength 22	sf22c
Shear strength 12	sf12s
Shear strength 23	sf23s
Matrix	
Normal modulus	Em
Poisson's ratio	Num
Coefficient of thermal expansion	Alfam
Thermal conductivity	Km
Heat capacity	Cm
Tensile strength	SmT
Compressive strength	SmC
Shear strength	SmS
Interphase	
Normal modulus	Ei
Poisson's ratio	Nui
Coefficient of thermal expansion	Alfai
Thermal conductivity	Ki
Heat capacity	Ci
Tensile strength	SiT
Compressive strength	SiC
Shear strength	SiS

This section has been broadly divided into three categories: (i) probabilistic analysis method definition, (ii) primitive variable uncertainty definition, and (iii) desired probabilistic output definition. The nature of input in the categories (i) and (iii) is straightforward and simple to understand. However, the input in the second category involve a few technical terms which are explained here. The uncertainty of a primitive variable is generally defined using a mean value, scatter and probability distribution type. Mean values of primitive variables are those input in the deterministic analysis input section 5.1.2 and constituent material properties in the resident data bank. Therefore, the user need not input the mean values of primitive variables in this section. Scatter in the primitive variables can be defined in terms of coefficient of variation (COV) or standard deviation. COV is defined as follows:

Coefficient of Variation: The standard deviation expressed as a fraction of mean value.

It is obvious from the definition that the COV is undefined when the mean value of a variable is zero. In the event that mean value is 0.0, the scatter has to be defined in terms of a standard deviation. For example, in the analysis of ceramic matrix composites, the ply angle orientation can be 0.0 degree. Therefore, uncertainty of ply angle has to be defined in terms of standard deviation.

The programmed distribution types and their assigned numbers in PCEMCAN are given below:

Distribution Type	Assigned Number	Availability status in PCEMCAN
Weibull	1	Available
Normal	2	Available
Extreme Value Type I	3	Available
Lognormal	4	Available
chi-square	5	Will be available later in future versions
Frechet	8	Available
Truncated Weibull	9	Will be available later in future versions
Truncated Normal	10	Will be available later in future versions

The detailed requirement for all these input categories are described in the following sections.

5.1.3.1 Probabilistic Analysis Method Definition

Method imethod nsamp iseed

This card defines the probabilistic analysis method selected for the analysis. Currently, the first order analysis, advanced first order analysis, and conventional Monte Carlo analysis are available in the program. Theoretical details on different analysis methods are given in reference 9. The first field contains mnemonic METHOD (Only first four characters may be input). The remaining fields are:

imethod	= 1	for first order analysis
	= 2	for advanced first order analysis
	= 6	for conventional Monte-Carlo analysis
nsamp	=	number of samples. This field is required for Monte-Carlo analysis.
iseed	=	seed for random samples. The input in this field is required for Monte-Carlo analysis only.

Typical EXAMPLES for this record are:

```
METH 1
Method 2
meth 6, 1000, 2543
METHOD 6 10000 4673
```

In the first example above, the first order analysis is chosen and advanced first order analysis in the second example. The third example is for Monte-Carlo analysis with 1000 samples and the random seed being 2543 whereas the last example selects Monte-Carlo analysis method with 10000 samples and 4673 as the seed for the random number generator. Note that only first four characters for the keyword have been input in the third example.

5.1.3.2 Primitive Variables Uncertainty Definition Record

Currently all variables (except loads) that are used to characterize material properties on a point basis have been included in PCEMCAN as random variables. Primarily there are two types of such variables: (i) those describing the ply geometry such as ply thickness and ply angle, (ii) material related variables such as fiber volume ratio, void volume ratio, interface thickness, and constituent material properties. These variables are listed in Table 5.1.3.1. The description of input to define uncertainties is given in the following sections.

5.1.3.2.1 Ply Geometry Description Variable Uncertainty Definition

Record Group:

Record 1: PVNAME
Record 2: SCAT IDIS

Uncertainties associated with the ply thickness and ply orientation angle are defined in this portion of input. A record group containing two record lines are required for each primitive variable: the first record line contains mnemonic describing the primitive variable (PVNAME) and the second line contains scatter (SCAT) and distribution type (IDIS). The definition of scatter and available distribution types are given in section 5.1.3. The legal primitive variable names and their symbols are given in Table 5.1.3.1. Remember that at least the first four characters of each variable name need to be input, however the symbol must be complete. <u>A note of caution to be given here is that the scatter for ply angle is input in terms of standard deviation</u>. Also, the current version of the code assumes that the ply description variable for all the plies are fully correlated. Detailed description of correlation is given in reference 5. Therefore, only one set of values for the scatter and distribution type is required for each ply description primitive variable. Future versions of the PCEMCAN code will have the capability for partially correlated ply description variables. Typical examples of input record groups are given below:

Ply Thickness	0.05	NORMAL
Ply Angle	1.0	LOG NORMAL
Plth	0.05	2
Pang	1.0	4

In the above first two examples ply thickness and ply angle have been chosen as random variables. Ply thickness is normally distributed random variable and has 5 percent COV whereas the ply angle has 1 degree standard deviation and log normal distribution. The last examples are same as the first two except that they are input using different format.

5.1.3.2.2. Material Property Variables Uncertainty Definition

The variables related to the material properties are fiber volume ratio (FVR), void volume ratio (VVR), interface thickness (ti), fiber properties, matrix properties and interface properties. Uncertainties in the FVR, VVR and interface thickness is defined using the following record group format:

Record 1:	PVNAME		
Record 2:	NM	SCAT	IDIS

PVNAME	describes mnemonic or symbol for FVR, VVR or interface thickness
NM	material no.
SCAT	scatter in terms of coefficient of variation
idis	distribution type

Examples:

```
fiber volu ratio
        1    0.04        1
 Vvr
        2    0.02        normal
 ti
        1    0.07        4
interphase thickness
        6    0.03        Weibull
```

In the examples above the fiber volume ratio, the void volume ratio, and interphase thickness are selected as random variable. The FVR is for material ID 1 with 4 percent COV and Weibull distribution. The VVR is for material ID 2 and has 2 percent COV and is Normally distributed. In the third and fourth examples, the interphase thickness for material ID 1 has 7 percent COV with Log-Normal distribution and for material ID 6 has 3 percent COV with Weibull distribution respectively.

The constituent material property uncertainty is defined using the following record group format:

Record 1	CONST_NAME	NM	
Record 2	CONST_PROP_NAME	SCAT	IDIS
.	.	.	.
.	.	.	.
.	.	.	.
Record n	CONST_PROP_NAME	SCAT	IDIS

where,

CONST_NAME	-	Name of the constituent. The legal names are Fiber, Matrix or Interface.
NM	-	Material No.
CONST_PROP_NAME	-	Name of the CONST_NAME property for which uncertainty is defined.
SCAT	-	Scatter in the CONST_PROP_NAME
IDIS	-	Distribution type

CONST_PROP_NAME can be described in the format text or related symbol as given in Table 5.1.3.1. The typical examples for material property uncertainty input is given below:

Fiber	1	
normal modulus	0.05	2
thermal conductivity	0.06	1
sf11T	0.04	4
sf23s	0.025	weib

In the above example the random variables for the fibers of material ID 1 are normal modulus (5 percent COV and normal distribution), thermal conductivity (COV=6 percent and Weibull distribution), tensile strength in the longitudinal direction (COV=4 percent and Lognormal distribution) and out of plane shear strength (COV=2.5 percent and Weibull distribution) have been selected in the analysis.

matrix	5	
norm modu	0.035	normal
comp stre	0.04	lognormal
alfam	0.036	2

In the above example the matrix related random variables for the material ID 5 are normal modulus (COV=3.5 percent, Normal distribution), compressive strength (COV=4 percent and Lognormal distribution) and coefficient of thermal expansion coefficient (COV=3.6 percent and Normal distribution) have been selected.

Interphase	2	
coef therm expa	0.05	2
SdT	0.07	Weibull

The above example describes selected interphase related random variables for the material ID 2. These are coefficient of thermal expansion (COV=5 percent and Weibull distribution) and tensile strength (COV=7 percent and Weibull distribution).

5.1.3.3 Probabilistic Output Definition

Cumulative probability distribution function (CDF) of the composite properties listed in Table 5.1.3.3.1 can be computed upon requesting for their probabilistic output. Also, the sensitivity of primitive random variables to the composite property probability are computed. Probabilistic output for more than one composite property can be computed in one single run. The probabilistic output is printed in 'symbol.out' file and the summarized CDF and sensitivity are printed in the 'symbol.mov' file. The format for the probabilistic output request record group is given below:

Record 1: PRIN
Record 2: SYMB1
Record 3: SYMB2

. .
. .
. .
n: SYMBn

Where PRIN - mnemonic for print option and is always = PRIN
SYMBn - is the composite material property symbol name from Table 5.1.3.3.1

TABLE 5.1.3.3.1 LIST OF COMPOSITE MATERIAL PROPERTIES SYMBOLS

Composite material property	Symbol
Coefficient of thermal expansion 11	CTE11
Coefficient of thermal expansion 22	CTE22
Coefficient of thermal expansion 33	CTE33
Heat conductivity 11	HK11
Heat conductivity 22	HK22
Heat conductivity 33	HK33
Heat capacity	HHC
Composite modulus 11	EC11
Composite modulus 22	EC22
Composite modulus 33	EC33
Composite modulus 12	EC12
Composite modulus 23	EC23
Composite modulus 31	EC31
Composite Poisson's ratio 12	NUC12
Composite Poisson's ratio 21	NUC21
Composite Poisson's ratio 13	NUC13
Composite Poisson's ratio 31	NUC31
Composite Poisson's ratio 23	NUC23
Composite Poisson's ratio 32	NUC32

5.1.3.4 End of Probabilistic Input Record

The probabilistic input data can be terminate by the 'END" card. However, there is no necessity to input this card since the program scans the end of file mark. This is not a mandatory card.

5.2 Resident Constituent Material Properties Data Bank

PCEMCAN utilizes a databank of material properties of several constituent (fiber/matrix/interphase) materials. This databank can be updated when new constituent properties become available. The primary advantage of this databank is that the user does not have to provide constituent material properties every time an analysis is carried out. The user merely specifies four-letter code names for the fiber and matrix, and the thickness of the interphase as a fraction of fiber diameter to make up a composite. The program then retrieves all the constituent material properties required to carry out the analysis.

The databank is organized into three sections: the first for fiber properties, the second for matrix properties, and the third for interphase properties. Each section ends with an "OVER" record. Each section is divided into several subsections depending upon the number of constituent properties defined within that section. There is no limit on the number of constituents within a section, i.e. there is no limit on the number of constituents.

The format of the data bank has been structured for easy interpretation so as to enable the user to expand or modify its content readily. In the non-linear material model, there are various exponents that define the functional dependence of a material property on a given variable, such as temperature, stress, etc. For any given constituent, a set of exponents have to be input in the data bank.

The number of records defining the material properties (fiber/matrix/interface) within a constituent section are fixed and their order as well as formats are defined in the subsequent paragraphs. However, it is important to note that the order of sections must be as shown above and the order of data records, format and units of a respective property must be in compliance with the descriptions given below:

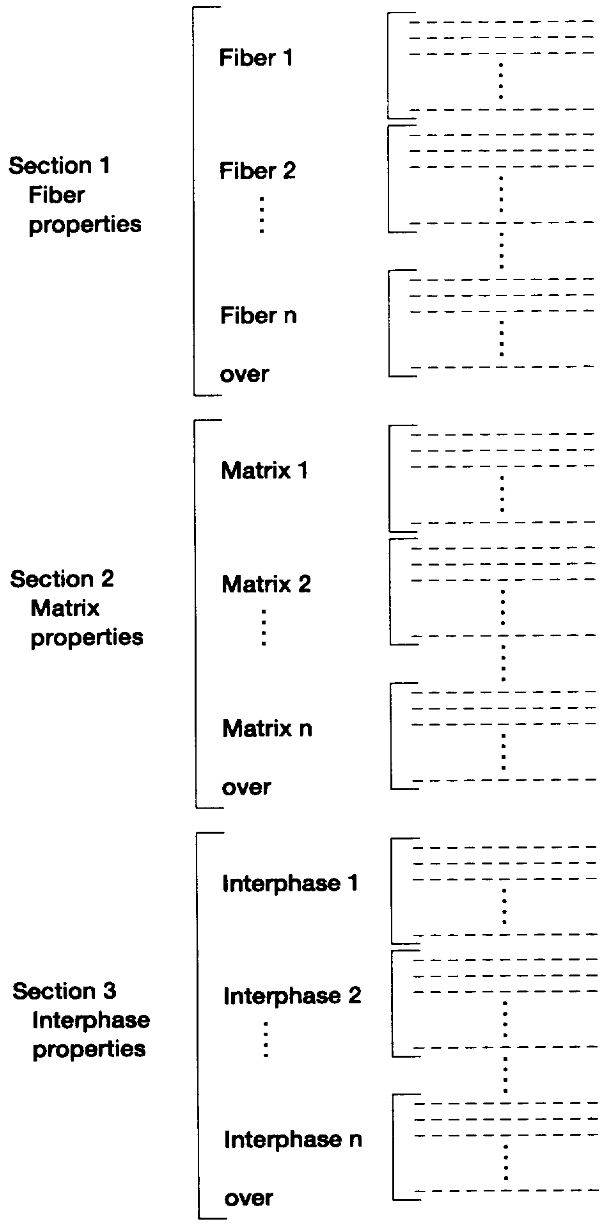

Figure 5.2.1.—Resident data bank file structure.

5.2.1 Fiber Properties Input Data Records

Record 1:	FKEY	(1X, A4)
	FKEY-Keyword	defining the fiber name

Records 2, 3, 4	(Title)	(A80)

Each record is used to input titles for the fiber. These are used for reference only.

Record 5 through 25:

FPROP_NAME, FPSYMB, VALUE, UNIT (A39, A11, E12.5, A18)

FPROP_NAME	-	Name of the fiber property
FPSYMB	-	Fiber property symbol
VALUE	-	Value of the fiber property
UNIT	-	Unit of the fiber property

The order in which different fiber properties in records 5 to 25 should be input is given below (note that the values of different properties given are for the example purpose only and are not actual values of some material):

NUMBER OF FIBERS	Nf	0.100E+01	—
DIAMETER	Df	0.700E-02	inches
WEIGHT DENSITY	Rhof	0.108E+00	lb/in**3
MELTING TEMPERTURE	Tempmf	0.450E+04	deg. F
NORMAL MODULUS (11)	Ef11	0.566E+08	psi
NORMAL MODULUS (22)	Ef22	0.566E+08	psi
POISSON'S RATIO (12)	Nuf12	0.170E+00	—
POISSON'S RATIO (23)	Nuf23	0.170E+00	—
SHEAR MODULUS (12)	Gf12	0.242E+08	psi
SHEAR MODULUS (23)	Gf23	0.242E+08	psi
COEF. THERMO. EXP. (11)	Alfaf11	0.230E-05	in/in/^{o}F
COEF. THERMO. EXP. (22)	Alfaf22	0.230E-05	in/in/^{o}F
THERMAL CONDUCTIVITY (11)	Kf11	0.127E+02	btu/hr/^{o}F/in
THERMAL CONDUCTIVITY (22)	Kf22	0.127E+02	btu/hr/^{o}F/in
HEAT CAPACITY	Cf	0.300E+00	btu/lb
TENSILE STRENGTH (11)	Sf11T	0.360E+06	psi
COMPRESSIVE STRENGTH (11)	Sf11C	0.486E+06	psi
TENSILE STRENGTH (22)	Sf22T	0.295E+06	psi
COMPRESSIVE STRENGTH (22)	Sf22C	0.486E+06	psi
SHEAR STRENGTH (12)	Sf12S	0.143E+06	psi
SHEAR STRENGTH (23)	Sf23S	0.143E+06	psi

Record 26 through 28		Title	(A80)
Record 29	SIGF011,	SIGF012	(6X, E10.3, T45, E10.3)
Record 30	SIGF022,	SIGF013	(6X, E10.3, T45, E10.3)
Record 31	SIGF033,	SIGF023	(6X, E10.3, T45, E10.3)

where	SIGF011	-	Initial (reference) stress 11 (psi)
	SIGF022	-	Initial (reference) stress 22 (psi)
	SIGF033	-	Initial (reference) stress 33 (psi)
	SIGF012	-	Initial (reference) stress 12 (psi)
	SIGF013	-	Initial (reference) stress 13 (psi)
	SIGF023	-	Initial (reference) stress 23 (psi)

Record 32 through 34		TITLE	(A80)
Record 35:	SIGFDOT011,	SIGFDOT012	(6X, E10.3, T45, E10-3)
Record 36:	SIGFDOT022,	SIGFDOT013	(6X, E10.3, T45, E10-3)
Record 37:	SIGFDO7033,	SIGFDOT023	(6X, E10.3, T45, E10-3)

where	SIGFDOT011	- Initial (reference) stress rate 11 (psi/sec)
	SIGFDOT022	- Initial (reference) stress rate 22 (psi/sec)
	SIGFDOT033	- Initial (reference) stress rate 33 (psi/sec)
	SIGFDOT012	- nitial (reference) stress rate 12 (psi/sec)
	SIGFDOT013	- nitial (reference) stress rate 13 (psi/sec)
	SIGFDOT023	- Initial (reference) stress rate 23 (psi/sec)

Record 38 through 43 TITLE (A80)
Record 44 through 48

exp_temp, exp_stress, exp_stressrate, exp_temp_cycle, exp_mech_cycle, exp_time
(19X, 6(F5.2, 5X))

These records define the values of exponents related to different terms in the non-linear multi-factor material property behavior model for various fiber properties.

Records 44 thorugh 48 respectively define the exponents for the fiber modulii, Poisson's ratio, strength, thermal expansion coefficient and heat conductivity. Each of these exponents are described below:

exp_temp	-	exponent related to the temperature term
exp_stress	-	exponent related to the stress term
exp_stressrate	-	exponent related to the stress rate term
exp_tempcycle	-	exponent related to the thermal cycle term
exp_mechcycle	-	exponent related to the mechanical cycle term
exp_time	-	exponent related to the time term

Record 49 through 50 TITLE (A80)

A typical example of input for this sub-section is given below:

```
SICR  SIC FIBERS USED FROM NASA TM 101350, OCT. 1988.
     $
     $
     $
     NUMBER OF FIBERS          Nf      0.100E+01   —
     DIAMETER                  Df      0.700E-02   inches
     WEIGHT DENSITY            Rhof    0.108E+00   lb/in**3
```

MELTING TEMPERTURE	Tempmf	0.450E+04	deg. °F
NORMAL MODULUS (11)	Ef11	0.566E+08	psi
NORMAL MODULUS (22)	Ef22	0.566E+08	psi
POISSON'S RATIO (12)	Nuf12	0.170E+00	—
POISSON'S RATIO (23)	Nuf23	0.170E+00	—
SHEAR MODULUS (12)	Gf12	0.242E+08	psi
SHEAR MODULUS (23)	Gf23	0.242E+08	psi
COEF. THERMO. EXP. (11)	Alfaf11	0.230E-05	in/in/°F
COEF. THERMO. EXP. (22)	Alfaf22	0.230E-05	in/in/°F
THERMAL CONDUCTIVITY (11)	Kf11	0.127E+02	btu/hr/°F/in
THERMAL CONDUCTIVITY (22)	Kf22	0.127E+02	btu/hr/°F/in
HEAT CAPACITY	Cf	0.300E+00	btu/lb
TENSILE STRENGTH (11)	Sf11T	0.360E+06	psi
COMPRESSIVE STRENGTH (11)	Sf11C	0.486E+06	psi
TENSILE STRENGTH (22)	Sf22T	0.295E+06	psi
COMPRESSIVE STRENGTH (22)	Sf22C	0.486E+06	psi
SHEAR STRENGTH (12)	Sf12S	0.143E+06	psi
SHEAR STRENGTH (23)	Sf23S	0.143E+06	psi

INITIAL (REFERENCE) STRESSES, SIGMA0, IN PSI

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

INITIAL (REFERENCE) STRESS RATES, SIGMADOTO, IN PSI/SEC

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	n Temp	m Stress	l Str.Rate	p T-Cycles	q M-Cycles	r Time
MODULI	0.25	0.00	0.00	0.50	0.50	0.50
NU'S	0.25	0.25	0.25	0.50	0.50	0.50
STRENGTHS	0.08	0.00	0.00	0.50	0.50	0.50
ALFA'S	0.25	0.00	0.25	0.50	0.50	0.50
HEAT COND.	0.25	0.00	0.25	0.50	0.50	0.50

OVER FIBER PROPERITIES

5.2.2 Matrix properties Input Data Records sub-section

Record 1:	MKEY	(1X, A4)
	MKEY-Keyword	defining the matrix name
Records 2, 3, 4 (Title)		(A80)

Each record is used to input titles for the matrix. These are used for reference only.

Record 5 through 19: MPROP_NAME, MPSYMB, VALUE, UNIT
(A39, A11, E12.5, A18)

MROP_NAME	-	Name of the matrix property
MPSYMB	-	Matrix property symbol
VALUE	-	Value of the matrix property
UNIT	-	Unit of the matrix property

The order in which different matrix properties in records 5 through 19 should be input is given below:

WEIGHT DENSITY	Rhom	0.980E-01	lb/in**3
NORMAL MODULUS	Em	1.595E+07	psi
POISSON'S RATIO	Num	0.220E+00	—
COEF. THERMO. EXP.	Alfam	0.120E-05	in/in/°F
THERMAL CONDUCTIVITY	Km	0.290E+01	btu/hr/°F/in
HEAT CAPACITY	Cm	0.230E+00	btu/lb
TENSILE STRENGTH	SmT	0.110E+05	psi
COMPRESSIVE STRENGTH	SmC	0.165E+06	psi
SHEAR STRENGTH	SmS	0.800E+04	psi
MAX. TENSILE STRAIN	EpsmT	0.300E+00	
MAX. COMPRESSIVE STRAIN	EpsmC	0.300E+00	
MAX. SHEAR STRAIN	EpsmS	0.300E+00	
MAX. TORSION STRAIN	EpsmTOR	0.300E+00	
VOID THERMO. COND.	Kvoid	0.190E-01	btu/hr/°F/in
MELTING TEMPERTURE	Tempmm	0.400E+04	deg. °F

Record 20 through 22		Title	(A80)
Record 23	SIGM011,	SIGM012	(6X, E10.3, T45, E10.3)
Record 24	SIGM022,	SIGM013	(6X, E10.3, T45, E10.3)
Record 25	SIGM033,	SIGM023	(6X, E10.3, T45, E10.3)

where	SIGM011	-	Initial (reference) stress 11 in matrix (psi)
	SIGM022	-	Initial (reference) stress 22 in matrix (psi)
	SIGM033	-	Initial (reference) stress 33 in matrix (psi)
	SIGM012	-	Initial (reference) stress 12 in matrix (psi)
	SIGM013	-	Initial (reference) stress 13 in matrix (psi)
	SIGM023	-	Initial (reference) stress 23 in matrix (psi)

Record 26 through 28 TITLE (A80)
Record 29: SIGMDOT011, SIGMDOT012 (6X, E10.3, T45, E10.3)
Record 30: SIGMDOT022, SIGMDOT013 (6X, E10.3, T45, E10.3)
Record 31: SIGMDO7033, SIGMDOT023 (6X, E10.3, T45, E10.3)

whereSIGMDOT011	-	Initial (reference) stress rate 11 in matrix (psi/sec)
SIGMDOT022	-	Initial (reference) stress rate 22 in matrix (psi/sec)
SIGMDOT033	-	Initial (reference) stress rate 33 in matrix (psi/sec)
SIGMDOT012	-	Initial (reference) stress rate 12 in matrix (psi/sec)
SIGMDOT013	-	Initial (reference) stress rate 13 in matrix (psi/sec)
SIGMDOT023	-	Initial (reference) stress rate 23 in matrix (psi/sec)

Record 32 through 37 TITLE (A80)
Record 38 through 42

exp_temp, exp_stress, exp_stressmate, exp_temp_cycle, exp_mech_cycle, exp_time
(19X, 6(F5.2, 5X))

These records define the values of exponents related to different terms in the non-linear multi-factor material property behavior model for various matrix properties.

Records 38 through 42 respectively define the exponents for the matrix modulii, Poisson's ratio, strength, thermal expansion coefficient and heat conductivity. Each of these exponents are described below:

exp_temp	-	exponent related to the temperature term
exp_stress	-	exponent related to the stress term
exp_stressrate	-	exponent related to the stress rate term
exp_tempcycle	-	exponent related to the thermal cycle term
exp_mechcycle	-	exponent related to the mechanical cycle term
exp_time	-	exponent related to the time term

Record 43 through 44 TITLE (A80)

A typical example of input for this sub-section is given below:

RBSN NASA TM NO. 101350, OCT. 1988, APR. 11, 1991. (1)

$
$
$

WEIGHT DENSITY	Rhom	0.980E-01	lb/in**3
NORMAL MODULUS	Em	1.595E+07	psi
POISSON'S RATIO	Num	0.220E+00	—
COEF. THERMO. EXP.	Alfam	0.120E-05	in/in/°F
THERMAL CONDUCTIVITY	Km	0.290E+01	btu/hr/°F/in
HEAT CAPACITY	Cm	0.230E+00	btu/lb
TENSILE STRENGTH	SmT	0.110E+05	psi
COMPRESSIVE STRENGTH	SmC	0.165E+06	psi
SHEAR STRENGTH	SmS	0.800E+04	psi
MAX. TENSILE STRAIN	EpsmT	0.300E+00	

MAX. COMPRESSIVE STRAIN	EpsmC	0.300E+00	
MAX. SHEAR STRAIN	EpsmS	0.300E+00	
MAX. TORSION STRAIN	EpsmTOR	0.300E+00	
VOID THERMO. COND.	Kvoid	0.190E-01	btu/hr/°F/in
MELTING TEMPERTURE	Tempmm	0.400E+04	deg. °F

INITIAL (REFERENCE) STRESSES, SIGMA0, IN PSI

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

INITIAL (REFERENCE) STRESS RATES, SIGMADOT0, IN PSI/SEC

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	n Temp	m Stress	l Str.Rate	p T-Cycles	q M-Cycles	r Time
MODULI	0.10	0.00	0.00	0.50	0.50	0.50
NU'S	0.00	0.00	0.00	0.50	0.50	0.50
STRENGTHS	0.10	0.00	0.00	0.50	0.50	0.50
ALFA'S	0.55	0.00	0.00	0.50	0.50	0.50
HEAT COND.	0.50	0.00	0.00	0.50	0.50	0.50

OVER MATRIX PROPERITIES

5.2.3 Interphase properties Input Data Records sub-section

Record 1: IKEY (1X, A4)

IKEY-Keyword defining the interphase name

Records 2, 3, 4 (Title) (A80)

Each record is used to input titles for the interphase. These are used for reference only.

Record 5 through 19: IPROP_NAME, IPSYMB, VALUE, UNIT (A39, A11, E12.5, A18)

IPROP_NAME	-	Name of the interphase property
IPSYMB	-	Interphase property symbol
VALUE	-	Value of the interphase property
UNIT	-	Unit of the interphase property

The order in which different interphase properties in records 5 through 19 should be input is given below:

WEIGHT DENSITY	Rhod	0.980E-01	lb/in**3
THICKNESS	td	0.300E-01	in
NORMAL MODULUS	Ed	1.595E+07	psi
POISSON'S RATIO	Nud	0.220E+00	—
COEF. THERMO. EXP.	Alfad	0.120E-05	in/in/°F
THERMAL CONDUCTIVITY	Kd	0.290E+01	btu/hr/°F/in
HEAT CAPACITY	Cd	0.230E+00	btu/lb
TENSILE STRENGTH	SdT	0.110E+05	psi
COMPRESSIVE STRENGTH	SdC	0.165E+06	psi
SHEAR STRENGTH	SdS	0.800E+04	psi
MAX. TENSILE STRAIN	EpsdT	0.300E+00	
MAX. COMPRESSIVE STRAIN	EpsdC	0.300E+00	
MAX. SHEAR STRAIN	EpsdS	0.300E+00	
MAX. TORSION STRAIN	EpsdTOR	0.300E+00	
VOID THERMO. COND.	Kvoid	0.190E-01	btu/hr/°F/in
MELTING TEMPERTURE	Tempmd	0.400E+04	deg. °F

Record 20 through 22		Title	(A80)
Record 23	SIGI011,	SIGI012	(6X, E10.3, T45, E10.3)
Record 24	SIGI022,	SIGI013	(6X, E10.3, T45, E10.3)
Record 25	SIGI033,	SIGI023	(6X, E10.3, T45, E10.3)

where	SIGI022	-	Initial (reference) stress 11 in interphase (psi)
	SIGI022	-	Initial (reference) stress 22 in interphase (psi)
	SIGI033	-	Initial (reference) stress 33 in interphase (psi)
	SIGI012	-	Initial (reference) stress 12 in interphase (psi)
	SIGI013	-	Initial (reference) stress 13 in interphase (psi)
	SIGI023	-	Initial (reference) stress 23 in interphase (psi)

Record 26 through 28 TITLE (A80)
Record 29: SIGIDOT011, SIGIDOT012 (6X, E10.3, T45, E10.3)
Record 30: SIGIDOT022, SIGIDOT013 (6X, E10.3, T45, E10.3)
Record 31: SIGIDO7033, SIGIDOT023 (6X, E10.3, T45, E10.3)

where SIGIDOT011 - Initial (reference) stress rate 11 in interphase (psi/sec)
SIGIDOT022 - Initial (reference) stress rate 22 in interphase (psi/sec)
SIGIDOT033 - Initial (reference) stress rate 33 in interphase (psi/sec)
SIGIDOT012 - Initial (reference) stress rate 12 in interphase (psi/sec)
SIGIDOT013 - Initial (reference) stress rate 13 in interphase (psi/sec)
SIGIDOT023 - Initial (reference) stress rate 23 in interphase (psi/sec)

Record 32 through 37 TITLE (A80)
Record 38 through 42
exp_temp, exp_stress, exp_stressmate, exp_temp_cycle, exp_mech_cycle, exp_time

(19X, 6(F5.2, 5X))

These records define the values of exponents related to different terms in the non-linear multi-factor material property behavior model for various interphase properties.

Records 38 through 42 respectively define the exponents for the interphase modulii, Poisson's ratio, strength, thermal expansion coefficient and heat conductivity. Each of these exponents are described below:

exp_temp	-	exponent related to the temperature term
exp_stress	-	exponent related to the stress term
exp_stressrate	-	exponent related to the stress rate term
exp_tempcycle	-	exponent related to the thermal cycle term
exp_mechcycle	-	exponent related to the mechanical cycle term
exp_time	-	exponent related to the time term

Record 43 through 44 TITLE (A80)

A typical example of input for this sub-section is given below:

```
WEAK INTERFACE.  NEGLIGIBLE PROPERTIES. APR. 11, 1991. (1)
   $
   $
   $
   WEIGHT DENSITY            Rhod     0.116E-00   lb/in**3
   THICKNESS                 td       0.300E-01   inches
   NORMAL MODULUS            Ed       0.500E+06   psi
   POISSON'S RATIO           Nud      0.220E+00   —
   COEF. THERMO. EXP.        Alfad    0.110E-05   in/in/°F
   THERMAL CONDUCTIVITY      Kd       0.120E+01   btu/hr/°F/in
   HEAT CAPACITY             Cd       0.120E+00   btu/lb
   TENSILE STRENGTH          SdT      0.110E+05   psi
   COMPRESSIVE STRENGTH      SdC      0.145E+05   psi
   SHEAR STRENGTH            SdS      0.800E+04   psi
```

MAX. TENSILE STRAIN	EpsdT	0.120E+00	
MAX. COMPRESSIVE STRAIN	EpsdC	0.120E+00	
MAX. SHEAR STRAIN	EpsdS	0.120E+00	
MAX. TORSION STRAIN	EpsdTOR	0.120E+00	
VOID THERMO. COND.	Kvoid	0.190E-01	btu/hr/°F/in
MELTING TEMPERTURE	Tempmd	0.400E+04	deg. °F

INITIAL (REFERENCE) STRESSES, SIGMA0, IN PSI

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

INITIAL (REFERENCE) STRESS RATES, SIGMADOT0, IN PSI/SEC

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	n Temp	m Stress	l Str.Rate	p T-Cycles	q M-Cycles	r Time
MODULI	0.10	0.00	0.00	0.50	0.50	0.50
NU'S	0.00	0.00	0.00	0.50	0.50	0.50
STRENGTHS	0.10	0.00	0.00	0.50	0.50	0.50
ALFA'S	0.55	0.00	0.00	0.50	0.50	0.50
HEAT COND.	0.50	0.00	0.00	0.50	0.50	0.50

OVER INTERPHASE PROPERITIES

6.0 PCEMCAN Output Files:

PCEMCAN output is stored in different files depending upon the type of analysis selected. A brief description of output files and its contents is given below for each analysis type.

6.1 Deterministic Analysis Output:

Results computed for the deterministic analysis are stored in the file "pcem.out" in the directory where PCEMCAN was executed. The nature of output is controlled by the output options requested in the deterministic section of the primary input file. The size of the output file depends upon the print options chosen. Obviously, a more refined analysis with large number of load steps and detailed output option request would generate a bigger file. A typical output file is shown in Chapter 7 for demonstration problems. The majority of the output is self explanatory. Additionally, the stress strain curves in the longitudinal and transverse directions are also printed. The stress strain curve for the longitudinal and transverse direction are printed (for the deterministic analysis only) in the files named 'lstrstrn.dat' and 'tstrstrn.dat' respectively. Note the units of stresses in the stress-strain curve output files is ksi.

6.2 Probabilistic Analysis Output:

Results computed for the probabilistic analysis are stored mainly in three different files. File "pcem.out" contains the input uncertainties, and composite properties results for deterministic analysis as well as those for each perturbation of each random variable. Those results would enable the user to perceive how the composite properties vary with respect to changes in random variables (meaning the behavior of composite laminate). The other two files are named based on the label/symbol of the composite property for which a probabilistic analysis has been performed. The generic form of the file names are "symbol.out" and "symbol.mov" where symbol is for the composite property (table 5.1.3.3.1). For example, if the probabilistic analysis was performed for the composite modulus in 11 direction (ec11) then the output file names would be 'ec11.out' and 'ec11.mov'. The .out file contains detailed probabilistic analysis output whereas the .mov file contains a summary of probabilistic analysis output. The summary contains the cumulative probability distribution function and sensitivity factors. Although the user is generally interested in the summary, it is often advisable to go through the .out file to ascertain the convergence of results. The summarized results do not give any indication if the results have converged or not. Refer to section 7 on Demonstration Problems for more detailed information on the contents of the output files.

7.0 Demonstration Problems:

7.1 Deterministic analysis:

7.1.1 Problem Description

The problem modeled is a two-ply unidirectional composite composed of silicon carbide (SCS-6) fibers in a reaction-bonded silicon nitride matrix. The fiber volume ratio is 0.3, no voids are present and each ply has a thickness of 0.01 in. There is an interphase with a thickness of 3 percent of fiber diameter (or approx. 4 mm thk.). The interfacial bonding around the fiber diameter is 1.0, indicating the perfect bond. The stress-free temperature is taken as 1200 °F. The composite is cooled down from this stress-free temperature to room-temperature (70 °F), and then subjected to a monotonic loading in the longitudinal direction at room-temperature as shown in figure 7.1.1-1. Complete output at each load step is requested. Figure 7.1.1-2 shows the unit cell sub-structuring used for the problem.

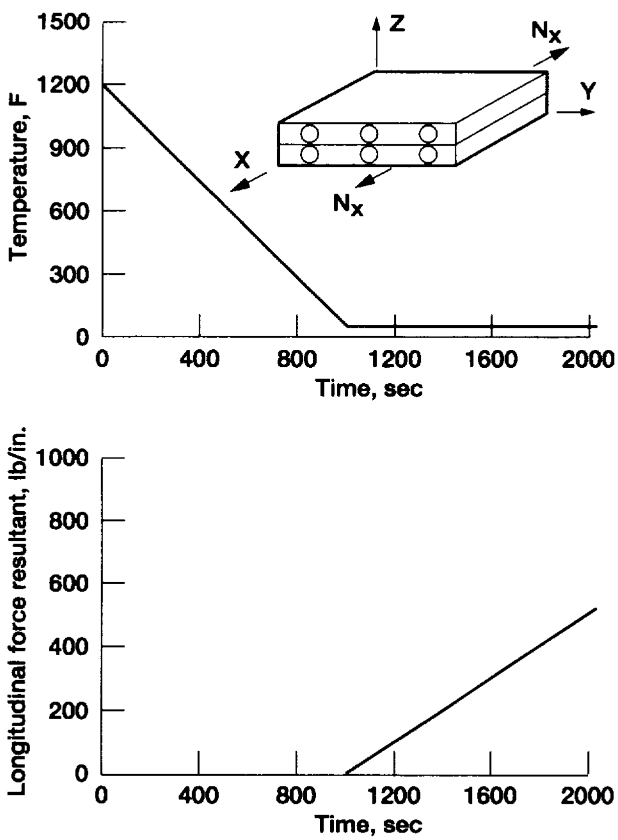

Figure 7.1.1-1.—Sample case loading history.

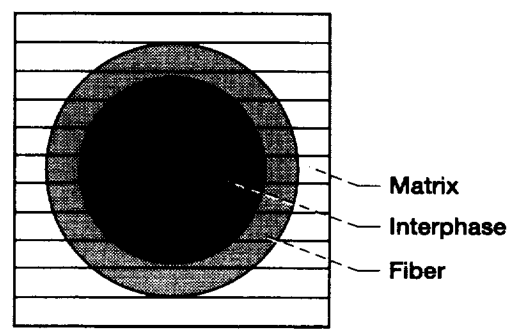

Figure 7.1.1-2.—Unit cell-substructuring for sample case (number of fiber divisions = 5, NFBDIV = 5 + 2 = 7).

7.1.2 Input file description.

As discussed in Chapter 5, there are two files required for the analysis purpose: (i) primary input file (pcemin.dat) and (ii) material data bank (new.dbk). These files for the sample problem are given below. Remember that the new.dbk file could remain the same for different problems provided it contains all the constituent properties used in the problem, thus it does not have to be created all the time. Also, line by line discussion of input has been given in this section, immediately after the input file.

Primary input file (pcemin.dat)

```
Line #  ----------------------------------------------------------------------
Field123456789012345678901234567890123456789012345678901234567890
             1         2         3         4         5         6

0     SAMPLE CASE FOR A TWO PLY SiC/RBSN COMPOSITE
1     DETE
2     $ NPLY,NMS,NDIV(NFBDIV+2)
3         2  1      7
4        PLY 1      1   0.0  .01
5        PLY 2      1   0.0  .01
6     $ Material Information here
7      MATCRD     1  0.30  0.00SICRRBSN
8     $ PRINT OPTIONS HERE
9       PRINT    ALL
10    $ PRINTING FREQUENCY HERE
11    PRINTOPT   ALL
12    $ INTERPHASE DETAILS
13    INTRFACE     1  0.03
14    $ Interfacial Bonding 2 lines per ply
15      1.00  1.00  1.00  1.00  1.00  1.00  1.00
16      1.00  1.00  1.00  1.00  1.00  1.00  1.00
17      1.00  1.00  1.00  1.00  1.00  1.00  1.00
18      1.00  1.00  1.00  1.00  1.00  1.00  1.00
19    $ Load Information has two segments process and loading
20     TMLOAD    -2
21      0.0  1000.   30
22     1200.  1200.
23      70.   70.
24      0.   0.  0.   0.0  0.0   0.0  0.0   0.0    00.
25       0.   00.0  0.  00.0  00.0  00.0  0.0   0.0    00.
26     1000.0  2000.   10
27      70.   70.
28      70.   70.
29       0.     0.  0.   0.0  0.0   0.0  0.0   0.0    00.
30      500.   0.0  0.  00.0  00.0  00.0  0.0   0.0    00.
31    $ End Data
```

The line numbers are given for reference purposes only and are not part of the input data file. Description of input in each line is given below:

Line No.	Description of Data
0.	Choose a problem title.
1.	Keyword 'DETE' indicates the code to perform deterministic analysis
2.	Comment card
3.	Number of plies is 2, number of material systems is 1 and Number of fiber and interphase division is 7.
4.	For the first ply, material identification number is 1, ply-angle is 0.0 and ply thickness is 0.01 in.
5.	For ply number 2, same as ply number 1.
6.	Comment card
7.	For the material identification, id no. 1, fiber volume ratio is 0.3, void volume ratio is 0.0 and fiber is SICR and matrix is RBSN (code names used in material databank for retrieving SCS-6 fiber and RBSN matrix material properties).
8.	Comment card.
9.	Requests all possible output.
10.	Comment card
11.	Output requests are printed for each load step of the analysis.
12.	Comment card.
13.	There is an interphase which is 3 percent of fiber diameter thick.
14.	Comment card
15-18	There is full interfacial bond around the fiber circumference
19.	Comment card
20.	There are two linear load profile segments.
21.	First segment starts at time 0.0, ends at time 1000. and is divided into 30 load-steps.
22.	The temperature in both the plies at the beginning of segment 1 (time=0) is 1200 F.
23.	The temperature in both the plies at the end of load segment 1 (time=1000.) is 70 F.
24.	The mechanical loads at the beginning of load segment are zero.
25.	The mechanical loads at the end of load segment are zero.
26.	Indicates that second linear load segment starts at time 1000 and ends at time 2000 and is divided into 10 increments.
27.	The temperature in both the plies at the beginning of segment 2 (time=1000) is 70 F.
28.	The temperature in both the plies at the end of segment 2 (time=2000) is 70 F.
29.	Indicates that there are no mechanical loads at the beginning of segment 2.
30.	Indicates that at the end of load segment 2, there is a longitudinal load of 500 lb./in. This means that the load increases monotonically from 0 at 1000 sec. to 500 lb/in. at 2000 sec.
31.	Comment card

Material properties data bank file (new.dbk file):

SICR SIC FIBERS USED FROM NASA TM 101350, OCT. 1988.
$
$
$

NUMBER OF FIBERS	Nf	0.100E+01 --
DIAMETER	Df	0.700E-02 inches
WEIGHT DENSITY	Rhof	0.108E+00 lb/in**3
MELTING TEMPERATURE	Tempmf	0.450E+04 ^{0}F
NORMAL MODULUS (11)	Ef11	0.566E+08 psi
NORMAL MODULUS (22)	Ef22	0.566E+08 psi
POISSON'S RATIO (12)	Nuf12	0.170E+00 --
POISSON'S RATIO (23)	Nuf23	0.170E+00 --
SHEAR MODULUS (12)	Gf12	0.242E+08 psi
SHEAR MODULUS (23)	Gf23	0.242E+08 psi
COEF. THERM. EXP. (11)	Alfaf11	0.230E-05 in/in/^{o}F
COEF. THERM. EXP. (22)	Alfaf22	0.230E-05 in/in/^{o}F
THERMAL CONDUCTIVITY (11)	Kf11	0.127E+02 btu/hr/^{o}F/in
THERMAL CONDUCTIVITY (22)	Kf22	0.127E+02 btu/hr/^{o}F/in
HEAT CAPACITY	Cf	0.300E+00 btu/lb
TENSILE STRENGTH (11)	Sf11T	0.295E+06 psi
COMPRESSIVE STRENGTH (11)	Sf11C	0.486E+06 psi
TENSILE STRENGTH (22)	Sf22T	0.295E+06 psi
COMPRESSIVE STRENGTH (22)	Sf22C	0.486E+06 psi
SHEAR STRENGTH (12)	Sf12S	0.143E+06 psi
SHEAR STRENGTH (23)	Sf23S	0.143E+06 psi

INITIAL (REFERENCE) STRESSES, SIGMA0, IN PSI

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

INITIAL (REFERENCE) STRESS RATES, SIGMADOT0, IN psi /sec

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	n	m	l	p	q	r		
		Temp	Stress	Stress Rate	Ther. Cycles	Mech. Cycles	Time	
MODULI		0.25	0.00	0.00	0.50	0.50	0.50	
NU'S		0.25	0.25	0.25	0.50	0.50	0.50	
STRENGTHS	0.08	0.00	0.00	0.50	0.50	0.50		
ALFA'S			0.25	0.00	0.25	0.50	0.50	0.50
HEAT COND.		0.25	0.00	0.25	0.50	0.50	0.50	

OVER FIBER PROPERTIES

RBSN NASA TM NO. 101350, OCT. 1988, APR. 11, 1991. (1)
$
$
$

WEIGHT DENSITY	Rhom	0.980E-01 lb/in**3
NORMAL MODULUS	Em	1.595E+07 psi
POISSON'S RATIO	Num	0.220E+00 --
COEF. THERM. EXP.	Alfam	0.120E-05 in/in/^{o}F
THERMAL CONDUCTIVITY	Km	0.290E+01 btu/hr/^{o}F/in
HEAT CAPACITY	Cm	0.230E+00 btu/lb
TENSILE STRENGTH	SmT	0.143E+05 psi
COMPRESSIVE STRENGTH	SmC	0.165E+05 psi
SHEAR STRENGTH	SmS	0.800E+04 psi
MAX. TENSILE STRAIN	EpsmT	0.300E+00
MAX. COMPRESSIVE STRAIN	EpsmC	0.300E+00
MAX. SHEAR STRAIN	EpsmS	0.300E+00
MAX. TORSION STRAIN	EpsmTOR	0.300E+00
VOID THERM. COND.	Kvoid	0.190E-01 btu/hr/^{o}F/in
MELTING TEMPERATURE	Tempmm	0.400E+04 ^{0}F

INITIAL (REFERENCE) STRESSES, SIGMA0, IN psi

NORMAL STRESSES		SHEAR STRESSES
11: 0.000E+00		12: 0.000E+00
22: 0.000E+00	13: 0.000E+00	
33: 0.000E+00	23: 0.000E+00	

INITIAL (REFERENCE) STRESS RATES, SIGMADOT0, IN psi/sec

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	Temp	Stress Stress	Ther. Rate	Mech. Cycles	Cycles	Time	
MODULI	0.10	0.00	0.00	0.50	0.50	0.50	
NU'S	0.00	0.00	0.00	0.50	0.50	0.50	
STRENGTHS	0.10	0.00	0.00	0.50	0.50	0.50	
ALFA'S		0.55	0.00	0.00	0.50	0.50	0.50
HEAT COND.	0.50	0.00	0.00	0.50	0.50	0.50	

OVER MATRIX PROPERTIES

WEAK INTERFACE. NEGLIGIBLE PROPERTIES. APR. 11,91(1)
$
$
$

WEIGHT DENSITY	Rhod	0.172E-00 lb/in**3
THICKNESS	td	0.300E-01 inches
NORMAL MODULUS	Ed	0.500E+06 psi
POISSON'S RATIO	Nud	0.200E+00 --
COEF. THERM. EXP.	Alfad	0.280E-05 in/in/^{o}F
THERMAL CONDUCTIVITY	Kd	0.390E+00 btu/hr/^{o}F/in
HEAT CAPACITY	Cd	0.120E+00 btu/lb
TENSILE STRENGTH	SdT	0.130E+05 psi
COMPRESSIVE STRENGTH	SdC	0.600E+05 psi
SHEAR STRENGTH	dS	0.800E+04 psi
MAX. TENSILE STRAIN	EpsdT	0.120E+00
MAX. COMPRESSIVE STRAIN	EpsdC	0.120E+00
MAX. SHEAR STRAIN	EpsdS	0.120E+00
MAX. TORSION STRAIN	EpsdTOR	0.120E+00
VOID THERMO. COND.	Kvoid	0.190E-01 btu/hr/^{o}F/in
MELTING TEMPERATURE	Tempmd	0.400E+04 ^{0}F

INITIAL (REFERENCE) STRESSES, SIGMA0, IN PSI

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

INITIAL (REFERENCE) STRESS RATES, SIGMADOT0, IN psi/sec

NORMAL STRESSES	SHEAR STRESSES
11: 0.000E+00	12: 0.000E+00
22: 0.000E+00	13: 0.000E+00
33: 0.000E+00	23: 0.000E+00

TABLE OF EXPONENTS

	Temp	Stress	Stress Rate	Ther. Cycles	Mech. Cycles	Time
MODULI	0.10	0.00	0.00	0.50	0.50	0.50
NU'S	0.00	0.00	0.00	0.50	0.50	0.50
STRENGTHS	0.10	0.00	0.00	0.50	0.50	0.50
ALFA'S	0.55	0.00	0.00	0.50	0.50	0.50
HEAT COND.	0.50	0.00	0.00	0.50	0.50	0.50

OVER INTERFACE PROPERTIES

7.1.3 Sample problem output file (deterministic analysis):

Results of the PCEMCAN simulation are written to a primary output file as mentioned before. Results for the composite properties for the sample input case shown in section 7.1.2 are performed here. The actual output file has not been given here since it is quite large. However, these results given in figure 7.1.3-1 demonstrate only the overall composite properties at the end of processing (at the end of step no. 31).

At this point, the program also outputs two files, lstrstrn.dat and tstrstrn.dat . The First file, lstrstrn.dat lists the composite strain/stress values in the X-direction at each load step, while the second file, tstrstrn.dat lists the composite strain/stress values in the Y-direction at each load step. These files are written in ASCII file format. Therefore, user can view them using a standard editor.

Figure 7.1.3-1 Composite Properties

COMPOSITEPROPERTIES

COMPOSITE PROPERTIES - VALID ONLY FOR CONSTANT TEMPERATURE THROUGH THICKNESS
LINES 1 TO 31 3-D COMPOSITE PROPERTIES ABOUT MATERIAL AXES
LINES 33 TO 62 2-D COMPOSITE PROPERTIES ABOUT STRUCTURAL AXES

1	RHOC	0.1032E+00	32	B2DEC	0.0000E+00
2	TC	0.2000E-01	33	CC11	0.2670E+08
3	CC11	0.2752E+08	34	CC12	0.2378E+07
4	CC12	0.3115E+07	35	CC13	0.0000E+00
5	CC13	0.3115E+07	36	CC22	0.1115E+08
6	CC22	0.1181E+08	37	CC23	0.0000E+00
7	CC23	0.2797E+07	38	CC33	0.4320E+07
8	CC33	0.1181E+08	39	EC11	0.2619E+08
9	CC44	0.4320E+07	40	EC22	0.1094E+08
10	CC55	0.4320E+07	41	EC12	0.4320E+07
11	CC66	0.4320E+07	42	NUC12	0.2132E+00
12	CTE11	0.1822E-05	43	NUC21	0.8906E-01
13	CTE22	0.1227E-05	44	CSN13	0.0000E+00
14	CTE33	0.1227E-05	45	CSN31	0.0000E+00
15	HK11	0.5438E+01	46	CSN23	0.0000E+00
16	HK22	0.3584E+01	47	CSN32	0.0000E+00
17	HK33	0.3584E+01	48	CTE11	0.1822E-05
18	HHC	0.2426E+00	49	CTE22	0.1227E-05
19	EC11	0.2619E+08	50	CTE12	0.0000E+00
20	EC22	0.1094E+08	51	HK11	0.5438E+01
21	EC33	0.1094E+08	52	HK22	0.3584E+01
22	EC23	0.4320E+07	53	HK12	0.0000E+00
23	EC31	0.4320E+07	54	HHC	0.2426E+00
24	EC12	0.4320E+07			
25	NUC12	0.2132E+00			
26	NUC21	0.8906E-01			
27	NUC13	0.2132E+00			
28	NUC31	0.8906E-01			
29	NUC23	0.2132E+00			
30	NUC32	0.2132E+00			
31	ZCGC	0.1000E-01			

7.2 Probabilistic analysis

7.2.1 Problem Description

The problem described in section 7.1.1 is now solved using probabilistic analysis. The random variables selected are fiber volume ratio (fvr), interphase thickness (t_i), fiber modulus in direction 11 (E_{f11}), matrix modulus (Em) and interphase normal modulus (E_i). The mean values of the fiber modulus and the interphase thickness are those defined the deterministic portion of the input. Values defined for E_{f11}, E_m, and E_i in the data bank are considered as their mean values. The uncertainty parameters for fvr, t_i, E_{f11}, E_m, and E_i are defined in the probabilistic input data portion of the file. Their respective scatter is 7, 5, 5, 10 and 5 percent (These values are chosen for the demonstration purpose). The probability distribution assumed for these variables is normal. Probabilistic characterization of the composite modulus in 11 direction (EC_{11}) is desired to be simulated.

7.2.2 Input File Description

As discussed in Chapter 5, there are two files required for the analysis purpose: (i) primary input file (pcemin.dat) and (ii) material data bank (new.dbk). The primary input file for the deterministic analysis given in the section 7.1.2 has been appended with the probabilistic input. The material data bank file remains same as that given in section 7.1.2. The input file and line by line description of the appended input is given immediately after the input file.

Primary Input File (pcemin.dat):

```
Line #  ______________________________

Field12345678901234567890123456789012345678901234567890123456789 0

              1          2          3          4          5          6

0     SAMPLE CASE FOR A TWO PLY SiC/RBSN COMPOSITE
1     PROB
2     $ NPLY,NMS,NDIV(NFBDIV+2)
3           2     1     7
4           PLY   1     1   0.0       .01
5           PLY   2     1   0.0       .01
6     $ Material Information here
7      MATCRD     1  0.30  0.00SICRRBSN
8     $ PRINT OPTIONS HERE
9      PRINT      NONE
10    $ PRINTING FREQUENCY HERE
11    PRINTOPT   ALL
12    $ INTERPHASE DETAILS
13    INTRFACE    1  0.03
14    $ Interfacial Bonding 2 lines per ply
15          1.00  1.00  1.00  1.00  1.00  1.00  1.00
16          1.00  1.00  1.00  1.00  1.00  1.00  1.00
17          1.00  1.00  1.00  1.00  1.00  1.00  1.00
18          1.00  1.00  1.00  1.00  1.00  1.00  1.00
19    $ Load Information has two segments process and loading
20    TMLOAD   -2
21          0.0   1000.      30
22          1200. 1200.
23          70.   70.
24          0.    0.     0.   0.0   0.0   0.0   0.0    0.0   00.
25          0.    00.0  0.    00.0  00.0  00.0   0.0  0.0   00.
26          1000.0      2000. 10
27          70.   70.
28          70.   70.
29    0.    0.    0.     0.0  0.0   0.0   0.0   0.0   00.
30          500.  0.0   0.    00.0  00.0  00.0  0.0   0.0   00.
31    $ End Data
32    $ Input for the probabilistic analysis data.
33    METHOD      1
34    Fiber  volume ratio
35                           1     0.07  2
36    Interface thickness
37                           1     0.05  2
38    Fiber                  1
39    Normal Modulus 11            0.05  2
40    Matrix             1
41    Normal modulus               0.10  2
42    Interface            1
```

```
43    normal modulus              0.05 2
44    PRIN
45    ec11
46    $ End Data
```

The line numbers are given for reference purposes only and are not part of the input data file. Description of input in each line is given below.

Line No.	Description of Data
0.	Choose a problem title
1.	Keyword 'PROB' indicates the code to perform probabilistic analysis
2-31.	Same as that for deterministic analysis in section 7.1.
32.	Comment card.
33.	Advanced first order probabilistic method is selected.
34.	Fiber volume ratio is chosen as random.
35.	The scatter for fiber volume ratio of material No. 1 is 7 percent, and is normally distributed.
36.	Interphase thickness is chosen as another random variable.
37.	The scatter for the interphase thickness is 5 percent and the distribution is normal.
38.	Indicates that the Fiber is the constituent for which random variables will be defined in the subsequent cards until a new constituent name or keyword is entered.
39.	Fiber normal modulus in the 11 direction has been defined as random variable. Its scatter is 5 percent and the distribution is normal.
40.	Indicates that the matrix is the constituent for which random variables will be defined in the subsequent cards until a new constituent name or keyword is entered.
41.	Matrix normal modulus has been defined as random variable. Its scatter is 10 percent and the distribution is normal.
42.	Indicates that the interphase is the constituent for which random variables will be defined in the subsequent cards until a new constituent name or keyword is entered.
43.	Interphase normal modulus has been defined as random variable. Its scatter is 5 percent and the distribution is normal.
44.	Keyword for the probabilistic analysis output selection option.
45.	Probabilistic analysis for the composite modulus in 11 direction is requested (EC11).
46.	Comment card.

As mentioned before the material property data bank file (new.dbk) remains same as that given in section 7.1.2

7.2.3 Sample problem output file (probabilistic analysis)

Results of the PCEMCAN simulation are written to three files. The primary output file (pcem.out), probabilistic analysis output file (symbol.out, in the demonstration problem it is ec11.out since the probabilistic analysis for EC11 is requested to be performed), and summarized probabilistic analysis output file (symbol.mov file, for demonstration problem 'ec11.mov'). The pcem.out file contains summarized composite properties for the deterministic and the perturbation analysis. These results are helpful to study and interpret probabilistic analysis output. Also, it will help an advanced user to evaluate an alternate strategy of analysis in case the probabilistic analysis does not converge. The file symbol.out ('ec11.out') contains the detailed probabilistic analysis output. Users should scan through this file to ascertain the convergence of probabilistic analysis. The symbol.mov ('ec11.mov') file contains the summary of probabilistic analysis results such as cumulative probability distribution function (CDF) and the sensitivity factors. Results in this file can be directly plotted for the graphical representations. Figure 7.2.3-1 shows the CDF of EC11 and the figure 7.2.3-2 shows sensitivity of random variables at 0.001 and 0.999 probability levels. The mean and standard deviation of the composite longitudinal modulus is 26.2 Mpsi and 1.53 Mpsi respectively. Thus the scatter is about 5.8 percent and the range is from 20.5 Mpsi to 31.9 Mpsi. It seen from the figure 7.2.3-2 that the composite modulus in the longitudinal direction is highly sensitive to the matrix modulus, fiber modulus, fiber volume ratio, and the interphase thickness. Since the sensitivity of EC11 to the matrix modulus is the highest, the reduction in the scatter of matrix modulus shall reduce the scatter in EC11 more than any other variables. However, next in the order are the fiber modulus and fiber volume ratio. Reduction in these variables will also help reduce the scatter in EC11. The sample output file 'ec11.mov' has been given below:

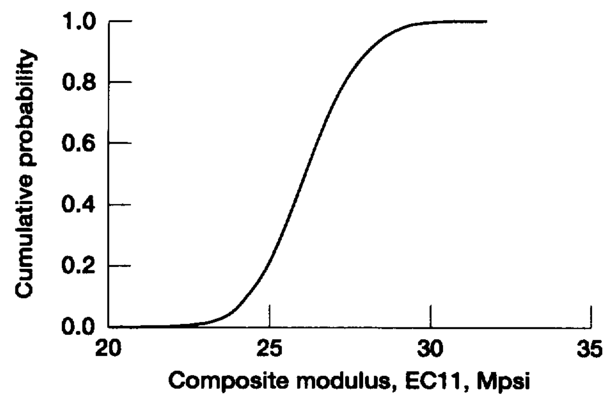

Figure 7.2.3-1.—CDF of CMC composite longitudinal modulus, EC11.

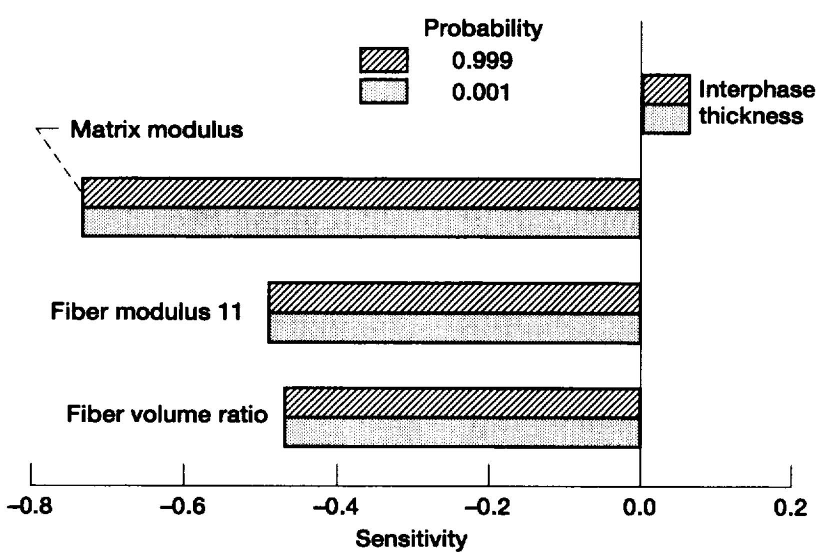

Figure 7.2.3-2.—Sensitivity of composite longitudinal modulus, EC11 to the randam variables.

Response (Z) median, mean, and std. dev. based on mean-value method

0.261921E+08	0.261953E+08	0.152774E+07

Response/Probability level: 18

Level	Z—value	u(std. normal)	Probability
1	0.205113E+08	-3.71909	0.000100000
2	0.214718E+08	-3.09025	0.001000000
3	0.226387E+08	-2.32635	0.010000000
4	0.236797E+08	-1.64485	0.050000000
5	0.242346E+08	-1.28155	0.100000000
6	0.246090E+08	-1.03643	0.150000000
7	0.253911E+08	-0.52440	0.300000000
8	0.261921E+08	0.00000	0.500000000
9	0.267807E+08	0.38532	0.650000000
10	0.272224E+08	0.67449	0.750000000
11	0.277752E+08	1.03643	0.850000000
12	0.281496E+08	1.28155	0.900000000
13	0.283909E+08	1.43953	0.925000000
14	0.287045E+08	1.64485	0.950000000
15	0.290649E+08	1.88079	0.970000000
16	0.297455E+08	2.32635	0.990000000
17	0.309123E+08	3.09025	0.999000000
18	0.318728E+08	3.71909	0.999900000

Most probable point (MPP) or design point

Level 1: (Z-value = 0.20511E+08, u = -3.7191, Probability = 0.000100000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2633438E+00	-1.745535	-0.469345
MAT.	1 FIBER NORM MODU 11	0.5143110E+08	-1.826465	-0.491105
MAT.	1 MATRIX NORM MODU	0.1161250E+08	-2.719433	-0.731209
MAT.	1 INTERPHASE NORM MODU	0.4999431E+06	-0.002274	-0.000611
MAT.	1 INTERPHASE THICK.	0.3034678E-01	0.231187	0.062162

Level 2: (Z-value = 0.21472E+08, u = -3.0903, Probability = 0.001000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT	1FVR	0.2695419E+00	-1.450388	-0.469343
MAT.	1 FIBER NORM MODU 11	0.5230505E+08	-1.517650	-0.491109
MAT.	1 MATRIX NORM MODU	0.1234591E+08	-2.259615	-0.731207
MAT.	1 INTERPHASE NORM MODU	0.4999528E+06	-0.001890	-0.000611
MAT.	1 INTERPHASE THICK.	0.3028818E-01	0.192123	0.062171

Level 3: (Z-value = 0.22639E+08, u = -2.3263, Probability = 0.010000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2770712E+00	−1.091850	−0.469341
MAT.	1 FIBER NORM MODU 11	0.5336673E+08	−1.142498	−0.491112
MAT.	1 MATRIX NORM MODU	0.1323685E+08	−1.701036	−0.731205
MAT.	1 INTERPHASE NORM MODU	0.4999644E+06	−0.001422	−0.000611
MAT.	1 INTERPHASE THICK.	0.3021698E-01	0.144654	0.062181

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2837881E+00	−0.771995	−0.469339
MAT.	1 FIBER NORM MODU 11	0.5431389E+08	−0.807814	−0.491116
MAT.	1 MATRIX NORM MODU	0.1403166E+08	−1.202722	−0.731203
MAT.	1 INTERPHASE NORM MODU	0.4999749E+06	−0.001006	−0.000611
MAT.	1 INTERPHASE THICK.	0.3015344E-01	0.102293	0.062190

Level 5: (Z-value = 0.24235E+08, u = -1.2816, Probability = 0.100000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2873689E+00	−0.601482	−0.469339
MAT.	1 FIBER NORM MODU 11	0.5481882E+08	−0.629393	−0.491118
MAT.	1 MATRIX NORM MODU	0.1445537E+08	−0.937073	−0.731202
MAT.	1 INTERPHASE NORM MODU	0.4999804E+06	−0.000784	−0.000611
MAT.	1 INTERPHASE THICK.	0.3011956E-01	0.079705	0.062194

Level 6: (Z-value = 0.24609E+08, u = -1.0364, Probability = 0.150000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2897848E+00	−0.486438	−0.469338
MAT.	1 FIBER NORM MODU 11	0.5515950E+08	−0.509012	−0.491119
MAT.	1 MATRIX NORM MODU	0.1474124E+08	−0.757841	−0.731201
MAT.	1 INTERPHASE NORM MODU	0.4999842E+06	−0.000634	−0.000611
MAT.	1 INTERPHASE THICK.	0.3009669E-01	0.064464	0.062198

Level 7: (Z-value = 0.25391E+08, u = -0.5244, Probability = 0.300000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.2948315E+00	−0.246120	−0.469337
MAT.	1 FIBER NORM MODU 11	0.5587115E+08	−0.257544	−0.491122
MAT.	1 MATRIX NORM MODU	0.1533841E+08	−0.383441	−0.731200
MAT.	1 INTERPHASE NORM MODU	0.4999920E+06	−0.000321	−0.000611
MAT.	1 INTERPHASE THICK.	0.3004893E-01	0.032620	0.062204

Level 8: (Z-value = 0.26192E+08, u = 0.0000, Probability = 0.500000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3000001E+00	0.000005	–0.469335
MAT.	1 FIBER NORM MODU 11	0.5660001E+08	0.000005	–0.491124
MAT.	1 MATRIX NORM MODU	0.1595001E+08	0.000007	–0.731198
MAT.	1 INTERPHASE NORM MODU	0.5000000E+06	0.000000	–0.000611
MAT.	1 INTERPHASE THICK.	0.3000000E-01	–0.000001	0.062211

Level 9: (Z-value = 0.26781E+08, u = 0.3853, Probability = 0.650000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3037977E+00	0.180844	–0.469334
MAT.	1 FIBER NORM MODU 11	0.5713555E+08	0.189241	–0.491126
MAT.	1 MATRIX NORM MODU	0.1639938E+08	0.281745	–0.731197
MAT.	1 INTERPHASE NORM MODU	0.5000059E+06	0.000236	–0.000611
MAT.	1 INTERPHASE THICK.	0.2996404E-01	–0.023973	0.062216

Level 10: (Z-value = 0.27222E+08, u = 0.6745, Probability = 0.750000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3066478E+00	0.316561	–0.469334
MAT.	1 FIBER NORM MODU 11	0.5753747E+08	0.331260	–0.491128
MAT.	1 MATRIX NORM MODU	0.1673663E+08	0.493184	–0.731196
MAT.	1 INTERPHASE NORM MODU	0.5000103E+06	0.000412	–0.000611
MAT.	1 INTERPHASE THICK.	0.2993705E-01	–0.041967	0.062220

Level 11: (Z-value = 0.27775E+08, u = 1.0364, Probability = 0.850000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3102151E+00	0.486432	–0.469333
MAT.	1 FIBER NORM MODU 11	0.5804054E+08	0.509023	–0.491130
MAT.	1 MATRIX NORM MODU	0.1715875E+08	0.757835	–0.731195
MAT.	1 INTERPHASE NORM MODU	0.5000158E+06	0.000634	–0.000611
MAT.	1 INTERPHASE THICK	0.2990326E-01	–0.064492	0.062225

Level 12: (Z-value = 0.28150E+08, u = 1.2816, Probability = 0.900000000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3126310E+00	0.601474	–0.469332
MAT.	1 FIBER NORM MODU 11	0.5838123E+08	0.629410	–0.491131
MAT.	1 MATRIX NORM MODU	0.1744462E+08	0.937063	–0.731194
MAT.	1 INTERPHASE NORM MODU	0.5000196E+06	0.000784	–0.000611
MAT.	1 INTERPHASE THICK.	0.2988038E-01	–0.079749	0.062228

Level 13: (Z-value = 0.28391E+08, u = 1.4395, Probability = 0.925000000)

R.V. name		X-value	Std. Dev. from Mean	Sensitivity factor
MAT.	1FVR	0.3141880E+00	0.675618	–0.469332
MAT.	1 FIBER NORM MODU 11	0.5860081E+08	0.707000	–0.491132
MAT.	1 MATRIX NORM MODU	0.1762886E+08	1.052577	–0.731194
MAT.	1 INTERPHASE NORM MODU	0.5000220E+06	0.000880	–0.000611
MAT.	1 INTERPHASE THICK.	0.2986563E-01	–0.089582	0.062230

Level 14: (Z-value = 0.28705E+08, u = 1.6449, Probability = 0.950000000)

R.V. name		X-value	Std. Dev. from Mean	Sensitivity factor
MAT.	1FVR	0.3162116E+00	0.771981	–0.469331
MAT.	1 FIBER NORM MODU 11	0.5888619E+08	0.807841	–0.491133
MAT.	1 MATRIX NORM MODU	0.1786832E+08	1.202706	–0.731193
MAT.	1 INTERPHASE NORM MODU	0.5000251E+06	0.001006	–0.000611
MAT.	1 INTERPHASE THICK.	0.2984645E-01	–0.102364	0.062233

Level 15: (Z-value = 0.29065E+08, u = 1.8808, Probability = 0.970000000)

R.V. name		X-value	Std. Dev. from Mean	Sensitivity factor
MAT.	1FVR	0.3185370E+00	0.882714	–0.469331
MAT.	1 FIBER NORM MODU 11	0.5921413E+08	0.923721	–0.491134
MAT.	1 MATRIX NORM MODU	0.1814348E+08	1.375221	–0.731192
MAT.	1 INTERPHASE NORM MODU	0.5000288E+06	0.001150	–0.000611
MAT.	1 INTERPHASE THICK.	0.2982442E-01	–0.117053	0.062236

Level 16: (Z-value = 0.29745E+08, u = 2.3263, Probability = 0.990000000)

R.V. name		X-value	Std. Dev. from Mean	Sensitivity factor
MAT.	1FVR	0.3229283E+00	1.091824	–0.469330
MAT.	1 FIBER NORM MODU 11	0.5983342E+08	1.142553	–0.491136
MAT.	1 MATRIX NORM MODU	0.1866310E+08	1.701004	–0.731191
MAT.	1 INTERPHASE NORM MODU	0.5000356E+06	0.001423	–0.000611
MAT.	1 INTERPHASE THICK.	0.2978281E-01	–0.144796	0.062242

Level 17: (Z-value = 0.30912E+08, u = 3.0903, Probability = 0.999000000)

R.V. name		X-value	Std. Dev. from Mean	Sensitivity factor
MAT.	1FVR	0.3304572E+00	1.450342	–0.469328
MAT.	1 FIBER NORM MODU 11	0.6089522E+08	1.517747	–0.491140
MAT.	1 MATRIX NORM MODU	0.1955400E+08	2.259558	–0.731189
MAT.	1 INTERPHASE NORM MODU	0.5000472E+06	0.001890	–0.000611
MAT.	1 INTERPHASE THICK.	0.2971144E-01	–0.192374	0.062252

Level 18: (Z-value = 0.31873E+08, u = 3.7191, Probability = 0.999900000)

R.V. name		X-value	Std. Dev. from	Mean Sensitivity factor
MAT.	1FVR	0.3366548E+00	1.745467	–0.469326
MAT.	1 FIBER NORM MODU 11	0.6176929E+08	1.826606	–0.491143
MAT.	1 MATRIX NORM MODU	0.2028736E+08	2.719351	–0.731187
MAT.	1 INTERPHASE NORM MODU	0.5000569E+06	0.002274	–0.000611
MAT.	1 INTERPHASE THICK.	0.2965267E-01	–0.231552	0.062260

8.0 Execution:

The code is written in standard Fortran 77 and is designed to be portable on different operating systems. It is a stand-alone computer code. It has been tested at NASA-Lewis Research Center on a Silicon Graphics Personal Iris. To run the code on a different machine, the source code should be compiled giving appropriate commands that initializes all the variables during compilation, (e.g., static option on SGI workstation). For specific compilation commands, the user is advised to contact the system administrator of that particular machine. However, a make file is also provided with the code that works for SGI workstations. Should a need arise to change the source files, this make file can be used to recompile and create a new executable file for SGI workstations running SGI operating systems.

The execution of the code is relatively straight-forward. The databank file is named new.dbk. The input file name is pcemin.dat. The input file and the databank file must reside in the directory in which PCECMAN is being executed. To run the code, issue the command at the prompt from the directory that contains the executable file named pcemcan and the databank file mentioned above. At the system prompt, issue the command -PCEMCAN

A sample input file is provided with the program. The output is stored in pcem.out and .mov files.

9.0 References

1. Mital, S.K., and Murthy, P.L.N. : CEMCAN-Ceramic Matrix Composites Analyzer User's Guide - Version 2.0, NASA TM–107187, April 1996.
2. Murthy, P.L.N., Ginty, C.A. and Sanfeliz, J.G. : Second Generation Integrated Composite Analyzer (ICAN) Computer Code, NASA TP–3290, 1993.
3. Lee, H.-J.; Gotsis, P.K.; Murthy, P.L.N. and Hopkins, D.A. : Metal Matrix Composite Analyzer (METCAN) User's Guide, Version 4.0, NASA TM–105244, 1991.
4. Murthy, P.L.N. and Chamis, C.C.: Towards the Development of Micromechanics Equations for Ceramic Matrix Composites via Fiber Substructuring, NASA TM–105246, February 1992.
5. Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion System Components, Annual Reports 1–6, NASA Contract NAS3–24389, 1985–1990, Southwest Research Institute, San Antonio, TX.
6. Murthy, P.L.N.; Chamis, C.C. and Mital, S.K. : Computational Simulation of Continuous Fiber-Reinforced Ceramic Matrix Composite Behavior, NASA TP–3602, July 1996.
7. Wu, Y.-T.: Computational Methods for Efficient Structural Reliability and Reliability Sensitivity Analysis, AIAA J., vol. 32, no. 8, Aug. 1994, pp. 1717–1723.
8. Murthy, P.L.N., Mital, S.K., Shah, A.R. : Probabilistic Micromechanics and Macromechanics for Ceramic Matrix Composites, NASA TM–4766, June 1997.
9. Southwest Research Institute, San Antonio, TX: NESSUS User's Manual, Vol. I and II.

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13. ABSTRACT ***(Maximum 200 words)***

PCEMCAN (Probabilistic CEramic Matrix Composites ANalyzer) is an integrated computer code developed at NASA Lewis Research Center that simulates uncertainties associated with the constituent properties, manufacturing process, and geometric parameters of fiber reinforced ceramic matrix composites and quantifies their random thermomechanical behavior. The PCEMCAN code can perform the deterministic as well as probabilistic analyses to predict thermomechanical properties. This User's guide details the step-by-step procedure to create input file and update/modify the material properties database required to run PCEMCAN computer code. An overview of the geometric conventions, micromechanical unit cell, nonlinear constitutive relationship and probabilistic simulation methodology is also provided in the manual. Fast probability integration as well as Monte-Carlo simulation methods are available for the uncertainty simulation. Various options available in the code to simulate probabilistic material properties and quantify sensitivity of the primitive random variables have been described. The description of deterministic as well as probabilistic results have been described using demonstration problems. For detailed theoretical description of deterministic and probabilistic analyses, the user is referred to the companion documents "Computational Simulation of Continuous Fiber-Reinforced Ceramic Matrix Composite Behavior," NASA TP-3602, 1996 and "Probabilistic Micromechanics and Macromechanics for Ceramic Matrix Composites," NASA TM 4766, June 1997.

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